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On the Precision of the Gravimetric Determination of the Geoid

R. A. HIRVONEN*

Abstract—On the basis of the gravity material available, the author studies two statistical functions: G_s = the rms (root mean square) anomaly in a square with side s, and E_s = the rms deviation of one actual point anomaly from the actual mean anomaly in a square with side s.

The function E_s is called the error of representation, for if inside a square there is only one observed anomaly and this anomaly is accepted to represent the mean anomaly of the entire square, a standard mean error E can be used for the estimation of accuracy. On the other hand, if there are no observations inside the square and the mean anomaly of the square is assumed to be zero, G can be used as the standard mean error.

For points or for very small squares, E is zero and G has a maximum value G_0. For a hemisphere, G is zero and E has a maximum value G_0. There is a critical size at about $s = 3°$, where $E = G$. When s is greater, it is not advisable to use the observed anomaly at a single station, as the representative of the mean anomaly of the square, because for zero the error to be expected is smaller. The weighted mean of zero and the observed anomaly is recommended.

Because the regions without any observations are still large, it is necessary to estimate the size of the smallest squares, where the mean anomaly can be assumed to be independent of the mean anomalies of the adjacent squares. On the basis of the present gravity data, an estimated value of $s = 30°$ seems to be acceptable.

Using the functions E and G and the accepted values $s = 3°$ and $s = 30°$, the precision obtainable for the gravimetric determination of the elevations N of the geoid (Stokes' formula) and of the deflections δ of the vertical (Vening Meinesz' formula) has been estimated. In the most favorable cases (Central Europe and the central parts of the United States) the standard mean error of N is ± 10 meters and that of δ $\pm 0.''85$. The former figure is almost entirely due to the great unexplored areas of the Earth; the latter depends half on these unexplored areas and half on the small gaps within a distance of 50° from the point where δ is computed.

THE ERROR OF REPRESENTATION

The precision obtainable in the gravimetric determination of the shape of the geoid depends mainly on the abundance and on the distribution of the observed gravity anomalies. The theoretical errors of the formulas of Stokes and Vening Meinesz are of minor significance. The errors caused by the methods of reduction to sea level can be considerable if the topography is very rugged around the point where the elevation of the geoid or the deflection of the vertical is to be computed; but the first important conclusions and applications can be reached by concentrating the computations on the regions with smooth anomalies.

In order to study the effects of the scarcity of observations, the probable magnitude and structure of the anomalies in the unobserved regions must be estimated. These estimates can be made by statistical analysis of the anomalies already observed, provided that the surveyed regions are representative enough for the entire Earth. The analysis has been performed by using the following functions: G_s, equal to the rms (root mean square) of mean anomalies of equal squares with side s, computable from a great sample of squares by the formula

$$nG_s^2 = \sum \Delta g_s^2$$

where n is the number of squares; and E_s, equal to the rms deviation of one point anomaly Δg from the mean anomaly Δg_s of the square, computable by the formula

$$nE_s^2 = \sum \sum (\Delta g - \Delta g_s)^2/\nu,$$

where ν is the number of stations within a square.

G_s obviously is a decreasing function of s. The maximum value G_0 for $s = 0$ shows how great the observed point anomalies generally are. We can assume that for a hemisphere ($s = r\sqrt{2\pi}$ in kilometers or $s = 148°$), G_s is zero, because the field of anomalies should not contain spherical harmonics of orders 0 and 1. The function E is related to the function G by the formulas

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$$E_s^2 = G_0^2 - G_s^2$$

or

$$G_s = G_0 \cos f$$

and

$$E_s = G_0 \sin f$$

where the angle f is an increasing function of s.

The first goal of the statistical analysis is to determine any one of the functions G_s, E_s or f with the constant G_0. As far as I know, the first estimation on E_s was attempted by *de Graaff-Hunter* [1935] on the basis of the pendulum observations in India. The density of the observation net was not great, 105 stations within an area of $8^\circ \times 14^\circ$, or less than one station for each square degree, but it was supposed that the isostatic anomalies were representative enough for this purpose. As a result, de Graaff-Hunter accepted a rather speculative function, $E_s = 11.3\sqrt{s}$ mgal (s in degrees), or, to be exact, $8.02(\sqrt{x^\circ} + \sqrt{y^\circ})$ as the error of representation for a rectangle with sides $2x^\circ$ and $2y^\circ$.

This formula, of course, is not valid beyond the range of the values of s within which it was estimated, that is, about $1^\circ < s < 10^\circ$. Specifically, it is evident that the mathematical form of de Graaff-Hunter's function cannot be correct for greater values of s because it tends to infinity instead of G_0. Also, the basic material of India alone might not be representative for the entire Earth, though the greater sample from the United States of America shown by *Rice* [1949] gives fair support to the de Graaff-Hunter results.

In Technical Paper 171 of the Mapping and Charting Research Laboratory of The Ohio State University Research Foundation, I published the results of samples taken from Scandinavia, France, and Mozambique, where dense if not wide gravimetric nets were available. These samples gave rather consistent values for E_s from $s = 0$ to $s = 1^\circ$. Samples from Russia, where larger areas with lesser density are available, showed an increasing discordance for $1^\circ < s < 5^\circ$. The extension of the function E_s for $5^\circ < s < 30^\circ$ was performed by using the isostatic mean anomalies published by *Tanni* [1948]. Finally a curve was drawn, showing the average values of E_s as obtained from the samples. The course of this curve for $s > 5^\circ$ was very uncertain.

According to the de Graaff-Hunter method, the precision obtainable by the application of the Stokes and Vening Meinesz formulas could be estimated by using the function obtained and by supposing that a homogeneous gravimetric net around the Earth with a spacing of 5 or 10° could be ascertained. This idea has two serious defects: (1) The homogeneous coverage has not yet been accomplished and will hardly ever be. Hence, this method does not give the precision obtainable on the data actually available. (2) Even if we had one gravity station at every 5 or 10°, the anomaly observed can hardly represent the mean anomaly of the surrounding square. A point anomaly often can be very great, but the mean anomalies of large squares are always smaller. Therefore, the function E_s can be used only when it is smaller than G_s; that is, up to the value $f = 45^\circ$. It is not necessary to establish the uncertain values of E_s for great values of s because the smaller values, G_s, can be established much more easily.

The following show the amended results of the samples published in Technical Paper 171. This time the values of G and G_0 have also been estimated. The figures in brackets have been computed from the formula $E^2 + G^2 = G_0^2$.

Results for Finland—These are based on 1300 stations covering an area of about five square degrees (spacing 6 km); free air anomalies in milligals; [$G_0 = \pm 16$].

E(10 km) = ±2.8	.....	.....
$E(0.^\circ16) = \pm 4.2$	$G(0.^\circ15) = \pm 15.5$	[$G_0 = \pm 16.1$]
$E(0.^\circ31) = \pm 6.5$	$G(0.^\circ32) = \pm 14.5$	[$G_0 = \pm 15.9$]
$E(0.^\circ47) = \pm 7.6$	[$G(0.^\circ47) = \pm 14.1$]	.....
$E(0.^\circ63) = \pm 10.0$	[$G(0.^\circ63) = \pm 12.5$]	.....
$E(0.^\circ95) = \pm 10.5$	[$G(0.^\circ95) = \pm 12.1$]	.....

Results for Sweden—These are based on 2000 stations, covering an area of $3^\circ \times 12^\circ$ (spacing 15 km); free air anomalies; [$G_0 = \pm 21$].

$E(0.^\circ24) = \pm 6.4$	$G(0.^\circ24) = \pm 18.1$	[$G_0 = \pm 19.2$]
$E(0.^\circ47) = \pm 9.5$	$G(0.^\circ48) = \pm 17.2$	[$G_0 = \pm 19.6$]
$E(0.^\circ95) = \pm 12.7$	$G(0.^\circ95) = \pm 16.6$	[$G_0 = \pm 20.9$]
$E(1.^\circ9) = \pm 17.0$	[$G(1.^\circ9) = \pm 12.3$]	.....
$E(2.^\circ8) = \pm 18.2$	[$G(2.^\circ8) = \pm 10.5$]	.....

Results for France—These are based on 1100 stations, covering an area of $4^\circ \times 5^\circ$ (spacing 10 km); free air anomalies.

$E(0.^\circ14) = \pm 3.4$	.....	.....
$E(0.^\circ34) = \pm 6.1$	$G(0.^\circ35) = \pm 9.2$	[$G_0 = \pm 11.0$]
$E(0.^\circ83) = \pm 9.5$	$G(0.^\circ83) = \pm 7.6$	[$G_0 = \pm 12.2$]
$E(3.^\circ7) = \pm 12.2$	.....	.....

Results for Russia—These are based on 1150 stations, covering an area of $10^\circ \times 15^\circ$ (spacing 32 km); free air anomalies; [$G_0 = \pm 26$].

$E(0.^\circ32) = \pm 6$	$G(0.^\circ32) = \pm 26$	[$G_0 = \pm 27$]
$E(0.^\circ82) = \pm 13$	$G(0.^\circ82) = \pm 23$	[$G_0 = \pm 26$]
$E(4.^\circ10) = \pm 22$	[$G(4.^\circ10) = \pm 14$]	.....

Results for India (according to de Graaff-Hunter)—These are based on 105 stations covering an area $8^\circ \times 14^\circ$; isostatic anomalies; $G_0 = \pm 30.8$.

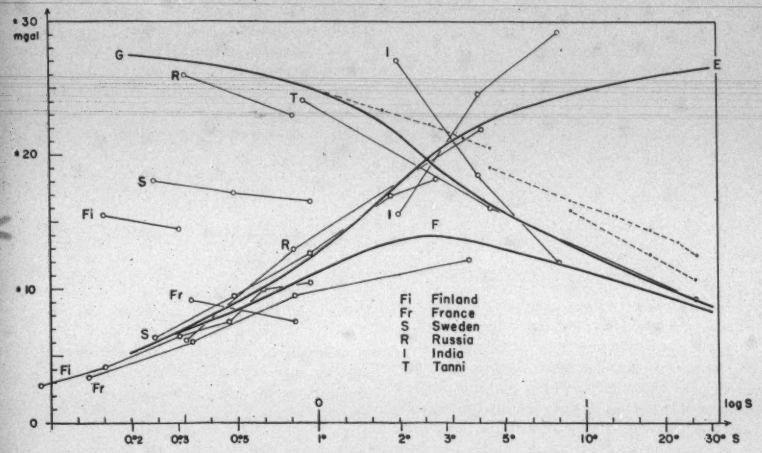

FIG. 1 – Functions of E (error of representation), G (mean anomaly of a square with side S), and F (equals GE/G_0)

$E(2°) = \pm 15.6 \quad G(2°) = \pm 27.1 \quad [G_0 = \pm 31.3]$
$E(4°) = \pm 24.6 \quad G(4°) = \pm 18.5 \quad [G_0 = \pm 30.8]$
$E(8°) = \pm 29.2 \quad G(8°) = \pm 12.0 \quad [G_0 = \pm 31.6]$

Isostatic mean anomalies of maps of Tanni *[1948]*—On Map III (1° × 1° squares of Eurasia) there are 734 squares with mean anomalies of high accuracy, ranging from −115 to +100. The rms anomaly is ±24.1. On Map II (5° × 5° squares of the entire world) there are 207 squares with mean anomalies of high accuracy, ranging from −50 to +30. The rms anomaly is ±16.1. On the basis of these squares the mean anomalies for only nine 30° × 30° squares can be computed with high accuracy. The rms anomaly is ±9.3.

Summary—These results have been collected in Figure 1. No one of the samples covers the entire range of s. If the spacing of the stations is small (or the density great), the samples give good values of E for the smallest squares, but in this case the samples do not cover extensive regions and the determination of E for large squares is not possible. Also the obtained values of G are not representative for the entire Earth. In fact, these samples happen to be situated in regions of small anomalies. On the other hand, taking samples of wide extent, the large spacing (small density) does not allow the computation of E for small squares, but the values of G are more representative.

When establishing the course of function E, the different samples give a compatible continuation of each other. On the other hand, for the function G only samples of wide extent can be used.

TABLE 1 – *Error of representation and related functions*

s	E	G	f	$\cos^2 f$	F	$F^2 s^2$	$G^2 s^2$
°			°				
0.0	±0.0	±28.0	0	1.00	±0.0	0.000	..
0.2	±5.4	±27.5	11	0.96	±5.3	0.001	..
0.5	±9.0	±26.5	19	0.90	±8.5	0.006	..
1.0	±12.7	±25.0	27	0.79	±11.3	0.039	..
2.0	±17.6	±21.8	39	0.60	±13.7	0.228	0.58
3.0	±20.8	±18.7	48	0.45	±13.9	0.530	0.96
5.0	±23.1	±15.8	56	0.32	±13.0	1.290	1.90
10.0	±24.9	±12.8	63	0.21	±11.4	3.960	5.00
30.0	±26.6	±8.7	72	0.10	±8.3	18.900	20.80

As a conclusive result, I have accepted the values shown in Table 1 to represent the functions E and G, shown by curves in Figure 1.

The critical size, where $f = 45°$ and $E = G$, is $s = 2.°6$. That means that if there is only one observed station inside a square with $s > 2.°6$, it is better to put the mean anomaly of the square equal to zero than to use the observed anomaly as the representative of the square. However, the best value obviously is the weighted mean of them both (observed value and zero)

$$\Delta g_s = (G_s/G_0)^2 \Delta g = \Delta g \cos^2 f$$

The standard mean error of this value is

$$F = G \sin f = GE/G_0 .$$

TABLE 2 – *Covariance of mean anomalies*

h	$C_{1,h}$	Gh	$C_{5,h}$	$G5h$	$C_{10,h}$	$G10h$
0	634	..	365	..	253	..
1	535	±25.2	255	±19.1	145	±15.9
2	437	23.5	200	16.6	71	12.8
3	393	22.3	152	15.4	39	10.8
4	336	21.3	120	14.4	26	..
5	286	20.6	75	13.5	..	..
6	231	..	35	12.6	..	..
7	..	..	3	..	..	..
9	90	..	..	..	..	..
12	1	..	..	..	..	..

THE COVARIANCE OF ANOMALIES

The anomalies within a square of moderate size have a positive correlation with each other. In other words, the product of any two anomalies is usually positive. The mean value of products of all pairs of anomalies with a constant distance d is called *covariance of anomalies*. It is a decreasing function of d. Provided that the covariance is the same in all directions it can be estimated with the aid of one-dimensional samples. This method has practical utility in that it is much easier to find densely observed profiles of anomalies than large squares with an even distribution of abundant observations. Moreover, there are long profiles that extend practically around the earth and thus furnish material that is more representative for the entire world than squares with the same number of points.

Instead of point anomalies, we can also use the mean anomalies of small squares. Let us take a set of mean anomalies v_1 , $v_2 \cdots v_n$ along a chain of small squares with equal sides s. Then the variance or the standard mean anomaly, denoted by G_s in the previous section, can be computed by the formula

$$nG_s^2 = \sum v_i^2$$

The covariance of two successive mean anomalies is

$$(n - 1)C_{s,1} = \sum v_i v_{i+1}$$

and the covariance of two anomalies with a distance of hs is

$$(n - h)C_{s,h} = \sum v_i v_{i+h}$$

The covariance $C_{s,h}$ is a decreasing function of h, with a maximum G_s^2 at $h = 0$. If the anomalies reveal an undulation with a constant wave length λ, there is a negative minimum for $hs = \lambda/2$, but usually $C_{s,h}$ remains close to zero when the distance hs exceeds a certain limit of correlation. Beyond this limit, any two anomalies are practically independent of each other.

Let us consider a large square of k^2 small squares with mean anomalies v. The rms anomaly G_{ks} of the large square can be computed by the formula

$$k^4 G_{ks}^2 = k^2 G_s^2 + 4k \sum_{h=1}^{k-1} (k - h) C_{s,h} + 4 \sum_{h=1}^{k-1} (k - h)^2 C_{s,h\sqrt{2}} + 8 \sum_{h=1}^{k-2} \sum_{i=h+1}^{k-1} (k - h) \cdot (k - i) C_{s,\sqrt{h^2+i^2}}$$

Here the covariances $C_{s,h}$ can be computed on the basis of long profiles as explained above, and the other covariances $C_{s,h\sqrt{2}}$ and $C_{s,\sqrt{h^2+i^2}}$ can be interpolated from the values $C_{s,h}$.

Using these formulas, I have computed some examples on the basis of the mean anomalies of Tanni:

(1) 1° × 1° squares (Map III), profile between points 41°N, 30°W, and 49°N, 60°E, with 90 squares. The results are shown in Table 2, columns $C_{1,h}$ and G_h .

(2) 5° × 5° squares (Map II), profile around the Earth, following the latitudes with best observations, 72 squares. The results are shown in columns $C_{5,h}$ and G_{5h} .

(3) 10° × 10° squares (on the basis of Map III), profile around the Earth as in the previous case with some meridional profiles, 72 squares. The results are shown in columns $C_{10,h}$ and G_{10h} .

These new values of G_s have been plotted lightly in Figure 1. They have not been used for the establishment of the final function G because the material involved here is less ample than that used in the previous section.

On the basis of Table 2, however, another important conclusion can be attained. The covariances $C_{1,12}$ and $C_{5,7}$ are almost zero, hence the limits of correlation are 12° and 35°. The material of the latter being more representative for the entire Earth, we can assume that the mean anomalies of the 30° × 30° squares have no correlation. This statement can not be proven immediately by the mean anomalies of the 30° × 30° squares themselves because the present gravity data do not render a sufficient number of samples. The 10° × 10° squares apparently do not quite confirm this statement, but, according to the original computations, the covariance actually was zero in the parallel profile at $hs = 40°$ and in the meridional profiles at $hs = 30°$.

In the next section this limit of correlation

will find the following application: The large unobserved areas of the Earth can be divided into squares of about 30° × 30° in size. If the mean anomaly of each square is assumed to be zero with a standard mean error $G_{30}°$, these errors can be considered to be independent of each other.

The correlations can also be used for the preparation of the anomaly map over the entire world. The small unobserved gaps must be filled by interpolated anomalies, and the border zones of the large gaps by extrapolated anomalies. The covariance function can help to decide in which way and how far the interpolation or extrapolation can be applied.

Computation of the Geoid

When the gravity anomalies Δg are known, the elevation of the geoid above the spheroid at any point P can be computed by Stokes' formula

$$N = \frac{1}{2\pi}\frac{R}{G}\int \Delta g S(\psi)\, d\sigma$$

The integration must be carried out over the entire surface σ of the sphere with radius 1. The constant $R/2\pi G = 1.035$ meters/mgal; ψ is the angle between the radii of P and $d\sigma$; and $S(\psi)$ is the Stokes function, obtainable from special tables [*Lambert* and *Darling*, 1936]. This function has a pole at $\psi = 0$. The integral, however, is finite because $S(\psi)\sin\psi = 2$ at $\psi = 0$.

In practice the surface σ must be divided into compartments. If the area of a compartment is q and the mean anomaly within the compartment Δg_q, the integration can be replaced by a summation

$$N = 1.035 \sum S \Delta g_q q.$$

This formula requires that S be considered as constant within the compartment; therefore q, corresponding to $d\sigma$ of the integral formula, must be rather small. When $\psi > 40°$, $q < 10° \times 10° = 0.03046$ will do because S varies slowly. For smaller values of ψ the compartments must be smaller.

Suppose now that each Δg_q has a mean error E. Then the mean error of N is

$$m(N) = 1.035 \sqrt{\Sigma S^2 E^2 q^2}.$$

I have carried out this summation as follows. The map of the world has been prepared in polar stereographic projection, using a separate sheet for each hemisphere. Into the squares q of the graticule the figures for $Q = E^2q^2$ have been written. A template on transparent paper shows the distances ψ from point P. The same template can be used for all points at the same latitude. The figures S^2 can be read from this template for each square. The products S^2Q are summed up.

The estimation of Q for observed regions requires no high accuracy and usually can be neglected, save in the immediate surroundings of P, which require a special treatment using local maps.

Suppose there are in the square q a few observations with an even distribution (a cluster of stations must be taken as one observation). If the number of observations is n, each of them represents an area $s^2 = q/n$, and the error of representation can be taken from Table 1, column F. The summation $\sum S^2F^2s^4$ over the square q can be carried out, assuming for S^2F^2 a constant mean value. Hence,

$$\sum S^2F^2s^4 = S^2F^2s^2q = S^2Q$$

where

$$Q = F^2s^2q$$

Suppose now that there is a large unobserved gap with an area $A = s^2$. Then the error of representation can be taken from Table 1, column G. The product $S^2G^2s^4$ involves now a mean value

$$S_A^2 = 1/n \sum S_q^2$$

where $n = s^2/q$. Hence

$$S_A^2G^2s^4 = \sum S_q^2Q$$

where

$$Q = G^2s^2q$$

In this way the values of Q can be computed for the squares q both over the observed and the unobserved areas. The final summation gives the standard mean error of N

$$m(N) = 1.035 \sqrt{\Sigma S^2 Q}$$

The accuracy of the gravimetric deflection of the vertical can be computed by using the same maps with values of Q. Instead of S^2, however, the values of $(dS/d\psi)^2$ must be read from the templates [*Sollins*, 1947], and the constant $R/2\pi G$ must be replaced by $\rho/2\pi G = 0.''0335$.

The computations have been based on the data that have been collected at the Mapping and Charting Research Laboratory, Columbus, Ohio. Figures 2 and 3 show the state in 1954 of observations on both hemispheres in the stereographic projection. As can be seen, the best results can be expected in the central parts of Europe and the United States of America. The largest gaps are situated on the oceans, especially on the

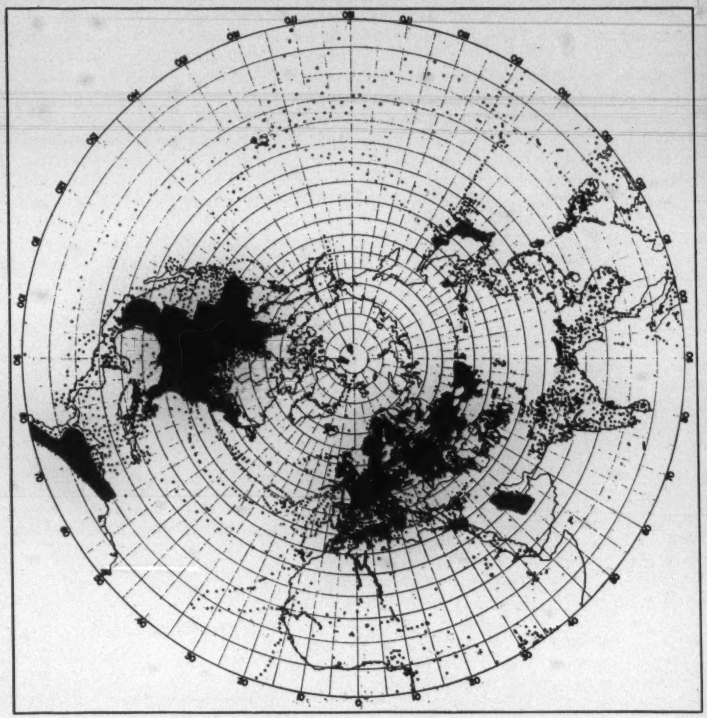

FIG. 2 – Northern hemisphere showing gravity observations available, 1954

southern parts. There are also some vast land areas still unobserved: eastern Sahara, Tibet, Siberia. It is very important to study the contribution of each gap on the computation of the geoid. Then we can plan the future expeditions that will effectively improve the results.

The following figures are the results of the first computations, showing the accuracy obtainable in the two most important regions, Europe and the United States.

Europe Point 50°N, 10°E near Frankfurt a.M.
$m(N) = \pm 10.1$ meters
$m(\delta) = \pm 0.''82$

North America Point 35°N, 90°W, near Memphis, Tenn.
$m(N) = \pm 10.4$ meters
$m(\delta) = \pm 0.''88$

Table 3 shows how the different parts of the Earth contribute to these results. Parts 1 and 2 consist of circles with radius $\psi = 35°$ around the two computed points. Parts 3 (Arctic Ocean, Siberia, Alaska, Northern Pacific), 4 (Southern Atlantic), 5 (Indian Ocean), and 6 (Southern Pacific) represent the areas with large unobserved areas.

The result $m(N) = \pm 10$ meters is exactly the same as obtained by *Tanni* [1948], in spite of the fact that at present there are many more observations available. The explanation is that the result is almost entirely due to the large unobserved areas of the Arctic section and the southern oceans, where only a few new observations have been obtained. We must note, however, that Tanni assumed the uncorrelated squares of the unobserved areas to be $10° \times 10°$ with ± 20

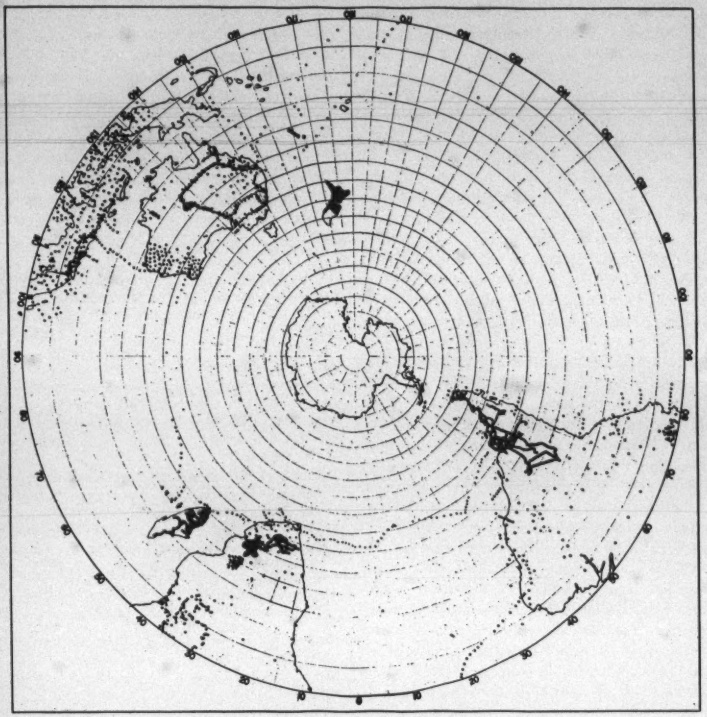

FIG. 3 – Southern hemisphere showing gravity observations available, 1954

mgal, while I have accepted 30° × 30° with ±9 mgal.

(Addendum; received August 1, 1955. In Publication 46 of the Finnish Geodetic Institute, 1955, Vening Meinesz gives an estimate of the effect of the unobserved distant areas (beyond $\psi = 27°$) to $m(N)$ and to $m(\xi)$ or $m(\eta)$. He states that on the 'observed half' of the Earth only ten regions can be found where the quantity Eq is ±30 mgal × (1000 km)². Assuming that this holds also for the unobserved half, the contribution of these regions to $m(N)$ becomes ±2.6 meters and to $m(\xi)$ or $m(\eta)$ ±0.″35. The former result differs considerably from our estimate $m(N)$ = ±10 meters. The explanation is that we have found on the observed half of the Earth 24 regions with Eq = ±9 mgal × (3300 km)². Thus our result must be greater by a factor

TABLE 3 – *Contribution of the Various Parts of the World to the Inaccuracy of the Gravimetric Determination of the Geoid*

Part	Region	Europe m^2		North America m^2	
		N	δ	N	δ
1	Europe	5	0.20	1	0.01
2	N. America	2	03	7	31
3	Arctic	10	04	12	03
4	Atlantic	17	08	12	10
5	Indian	27	12	42	12
6	S. Pacific	35	15	32	16
7	Remaining parts	5	05	3	05
Total m^2		101	0.67	109	0.78
m		±10.1	±0.82	±10.4	±0.88

$\sqrt{2.4} \times 0.3 \times 3.3^2 = 5$. In $m(\xi)$ the discrepancy is essentially reduced because Vening Meinesz uses for $ds/d\psi$ an average value $8.9/\sqrt{2} = 6.3$ instead of the correct value 2.0.)

As to the results $m(\delta) = \pm 0.''85$, the large distant gaps contribute only about a half of the total amount of m^2, while the remaining half is due mainly to the small gaps within $\psi < 50°$, because of the great values of $dS/d\psi$. As an example, the empty gap of the North Sea alone contributes about 0.05 to $m^2(\delta)$ for Central Europe, and that of the Labrador region about 0.09 to $m^2(\delta)$ for North America. A few observed points inside these small gaps would essentially reduce their effects, because the remaining errors would no longer be systematic, but would partly cancel each other.

When planning the future gravimetric surveys, the greatest emphasis should be laid on the exploration of the oceans of the southern hemisphere. This certainly is an immense task. Even if we want only profiles with a spacing of 15° through these areas, about 100,000 km of submarine cruises would be required. Then the values of Q would be reduced to half of their present size and $m(N)$ would be about ± 7 meters, $m(\delta)$ about $\pm 0.''7$. This is not a considerable gain for the special geodetic purposes discussed above, but there are many questions of a general nature which require information on the southern hemisphere. In addition to this, these profiles would give much more basic material for the statistical investigations that form the ground for this paper and that must be renewed in the future.

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Limiting Form of Taylor Series Used in Extrapolating Components of the Geomagnetic Intensity

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Abstract—In the extrapolation of geomagnetic components, a theoretical treatment of the Taylor series shows that the ratio of the absolute value of successive terms of the series approaches the limit h/a where h is the extrapolation distance and a is the radius of the Earth. Expressions are presented for the limiting form of the remainder after a certain finite number of terms of the series. These expressions, which comprise the product of a computed term and a binomial series, may be used to limit the number of partial derivatives that need to be computed.

Introduction—Recently, *Zmuda* and *McClung* [1955] reported a method of extrapolating the components of the intensity of the magnetic force. A Taylor series is used, in which the partial derivatives in the vertical direction are computed from data on the surface of the Earth. The expression for each partial derivative contains several terms, and it is the purpose here to examine, with the aid of spherical harmonics, the relative importance of these terms.

Method of extrapolation—In the region that is above or below the surface of the Earth but outside sources of magnetism, the components of the geomagnetic intensity F may be expanded in a series of solid spherical harmonics. In polar coordinates θ, ϕ, and r, the respective series are

$$X_n = -\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+2}\frac{\partial}{\partial\theta}f_n^m(\theta,\phi) \quad (1)$$

$$Y = -\sum_{n=1}^{\infty}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+2}\frac{1}{\sin\theta}\frac{\partial}{\partial\phi}f_n^m(\theta,\phi) \quad (2)$$

$$Z_n = \sum_{n=1}^{\infty}\sum_{m=0}^{n}(n+1)\left(\frac{a}{r}\right)^{n+2}f_n^m(\theta,\phi) \quad (3)$$

where X_n, Y, and Z_n are respectively the southern, eastern, and upward components; a is the radius of the Earth, approximately 6400 km; and $f_n^m(\theta,\phi)$ is defined by

$$f_n^m(\theta,\phi) = P_n^m(\cos\theta)(A_n^m\cos m\phi + B_n^m\sin m\phi) \quad (4)$$

In (4), $P_n^m(\cos\theta)$ is an associated Legendre function of the first kind, of degree n and order m; A_n^m and B_n^m are constants that are evaluated from an analysis of surface data. A recent harmonic analysis of the geomagnetic was made by *Vestine* and his collaborators [1947], who used a method of best fit by least squares to compute 48 coefficients, up to $n = m = 6$.

Note that X_n and Z_n are defined to be contrary in sign to the X and Z normally used in geomagnetism, for which the northward and downward directions are considered positive. The change was made in order to have the positive direction correspond to increasing θ and r.

In an alternative method of extrapolating components [*Zmuda* and *McClung*, 1955], each component is separately continued by a Taylor series in which the derivatives in the vertical direction are obtained from surface data of the components. This method does not give the detail of the harmonic analysis, marked by the separate harmonic terms, but the result obtained with it should equal that obtained by summing all the spherical harmonics.

The first partial derivatives in the vertical direction are obtained from the analytic expressions for the curl and divergence of the intensity. The respective partials are

$$\frac{\partial X_n}{\partial r} = \frac{1}{r}\left(\frac{\partial Z_n}{\partial\theta} - X_n\right) \quad (5)$$

$$\frac{\partial Y}{\partial r} = \frac{1}{r}\left(\frac{\partial Z_n}{\sin\theta\,\partial\phi} - Y\right) \quad (6)$$

which are obtained from the ϕ and θ component of the relation curl $\mathbf{F} = 0$; and

$$\frac{\partial Z_n}{\partial r} = -\frac{1}{r}\cdot\left(2Z_n + \frac{\partial X_n}{\partial\theta} + X_n\cot\theta + \frac{\partial Y}{\sin\theta\,\partial\phi}\right) \quad (7)$$

obtained from div $\mathbf{F} = 0$.

Differentiating with respect to r in (5), (6) and (7) gives, for the higher order partials of any order q, expressions which may be written as

$$\frac{\partial^q X_n}{\partial r^q} = \frac{1}{r}\left(\frac{\partial}{\partial\theta}\frac{\partial^{q-1}Z_n}{\partial r^{q-1}} - q\frac{\partial^{q-1}X_n}{\partial r^{q-1}}\right) \quad (8)$$

$$\frac{\partial^q Y}{\partial r^q} = \frac{1}{r}\left(\frac{\partial}{\sin\theta\,\partial\phi}\frac{\partial^{q-1}Z_n}{\partial r^{q-1}} - q\frac{\partial^{q-1}Y}{\partial r^{q-1}}\right) \quad (9)$$

and

$$\frac{\partial^q Z_n}{\partial r^q} = -\frac{1}{r}\left[D + (q+1)\frac{\partial^{q-1}Z_n}{\partial r^{q-1}}\right] \quad (10)$$

where

$$D = \frac{\partial}{\partial\theta}\frac{\partial^{q-1}X_n}{\partial r^{q-1}} + (\cot\theta)\frac{\partial^{q-1}X_n}{\partial r^{q-1}} + \frac{\partial}{\sin\theta\,\partial\phi}\frac{\partial^{q-1}Y}{\partial r^{q-1}} \quad (11)$$

Note (for example, by substituting the appropriate expression of (5), (6), or (7) into the equation for consecutive higher order partials) that the derivative with respect to r of any order is obtained from data on a single spherical surface. These partials are, of course, identical with those obtained by differentiating with respect to r the spherical harmonics of (1), (2), or (3).

The extrapolation of each component is effected by means of the Taylor series

$$C_{r=a+h} = C_{r=a} + h\left(\frac{\partial C}{\partial r}\right)_{r=a} + \cdots \quad (12)$$

where C is X_n, Y, or Z_n, and h is the extrapolation distance which may be either below or above the surface $r = a$.

When the partial derivatives are taken in the direction in which the variable increases, h is positive in an upward continuation and negative in a downward extrapolation.

Limiting ratio of successive terms—An association between the terms that are computed to form the partial derivatives in the vertical direction leads to a simple relation between ultimate successive terms of the Taylor series for the component. This relationship may be used to indicate the rapidity of convergence of the series and to compute the remainder after a finite number of terms in the series.

For example, consider the upward extrapolation of the X_n component by the Taylor series and in particular the magnitude of the terms constituting the expression for the qth vertical partial. By incorporating the representation of X_n by spherical harmonics, we may write these terms as

$$\left(\frac{\partial^q X_n}{\partial r^q}\right)_{r=a} = \frac{1}{a^q}\cdot\left[\sum_{n=1}^{\infty}\sum_{m=0}^{n}(-1)^{q-1}(n+1)(n+2)\cdots(n+q)\cdot\frac{\partial}{\partial\theta}f_n^m(\theta,\phi) + \sum_{n=1}^{\infty}\sum_{m=0}^{n}(-1)^{q+1}\cdot q(n+2)\cdots(n+q)\frac{\partial}{\partial\theta}f_n^m(\theta,\phi)\right] \quad (13)$$

Note that substituting (13) into (12) gives a power series in powers of $v = h/a$ which is convergent for $v^2 < 1$. The interval of convergence has been determined by applying the ratio test.

For any specific spherical harmonic of degree n, the contributions of both terms in (13) to the qth partial are always of the same sign. Also, the relative importance of the two terms is determined by the relative magnitude of q, the order of the derivative, and $n + 1$.

When the magnetic field being extrapolated is representable by a number of spherical harmonics, then the sign of the two terms in (13), each term a summation of spherical harmonics, may be different. Ultimately, for a finite number of harmonics, a partial derivative of order q may be taken so that

$$q \ll n + 1 \quad (14)$$

for all n's. In this case, the right-hand term in (13) is dominant and that equation, or (8), reduces to

$$\left(\frac{\partial^q X_n}{\partial r^q}\right)_{r=a} = -\frac{q}{a}\left(\frac{\partial^{q-1}X_n}{\partial r^{q-1}}\right)_{r=a} \quad (15)$$

Now, the Taylor series of (12) may be written as

$$X_{n(r=a+h)} = X_{n(r=a)} + h\left(\frac{\partial X_n}{\partial r}\right)_{r=a} + \cdots + \frac{h^s}{s!}\left(\frac{\partial^s X_n}{\partial r^s}\right)_{r=a} + R_X \quad (16)$$

where R_X, the remainder after $(s + 1)$ terms of the series, is

$$R_X = \frac{h^{s+1}}{(s+1)!}\left(\frac{\partial^{s+1}X_n}{\partial r^{s+1}}\right)_{r=a} + \cdots \quad (17)$$

Assuming that (15) is valid for $q > s$ and then substituting (15) in (17), one finds that R_X is given simply by

$$R_X = \frac{h^s}{s!}\left(\frac{\partial^s X_n}{\partial r^s}\right)_{r=a}(-v + v^2 - v^3 + \cdots) \quad (18)$$

where, as previously noted, $v = h/a$.

Adding unity to the bracketed series of (18) gives the well-known alternating infinite geometric series which converges to the limit

$$L = \frac{1}{1+v} \tag{19}$$

for values of v in the interval $v^2 < 1$.

From (18), it is seen that the ratio of the absolute values of successive terms of the series approaches the limit v and from (18) and (19) that the remainder converges to the limit

$$R_X = \frac{h^s}{s!}\left(\frac{\partial^s X_n}{\partial r^s}\right)_{r=a} \frac{-v}{1+v} \tag{20}$$

Similar arguments applied in the extrapolation of Y and Z_n by the Taylor series show that there too, the ratio of absolute values of successive terms is $v = h/a$, and the series converges for $v^2 < 1$. The remainder for the Y component is identical in form to that of the X_n component; that is

$$R_Y = \frac{h^s}{s!}\left(\frac{\partial^s Y}{\partial r^s}\right)_{r=a} (-v + v^2 - v^3 + \cdots) \tag{21}$$

or,

$$R_Y = \frac{h^s}{s!}\left(\frac{\partial^s Y}{\partial r^s}\right)_{r=a} \frac{-v}{1+v} \tag{22}$$

With Z_n the general expression in (10) reduces to

$$\left(\frac{\partial^q Z_n}{\partial r^q}\right)_{r=a} = -\frac{q+1}{a}\frac{\partial^{q-1} Z_n}{\partial r^{q-1}} \tag{23}$$

for

$$q + 1 \gg n \tag{24}$$

When (23) is valid for all q's greater than s, the remainder R_Z after $(s+1)$ terms of the Taylor series is

$$R_Z = \frac{h^s}{(s+1)!}\left(\frac{\partial^s Z_n}{\partial r^s}\right)_{r=a} \cdot[(s+2)(-v) + (s+3)(-v)^2 + \cdots] \tag{25}$$

which reduces to

$$R_Z = \frac{h^s}{(s+1)!}\left(\frac{\partial^s Z_n}{\partial r^s}\right)_{r=a} \left(\frac{1}{(1+v)^2} - 1 - \frac{sv}{1+v}\right) \tag{26}$$

In a downward continuation, h is negative, and all terms in (18), (21), and (25) are positive. The limit of the ratio of the successive terms of the Taylor series is still h/a, but now the respective remainders reduce to

$$R_X = \frac{h^s}{s!}\left(\frac{\partial^s X_n}{\partial r^s}\right)_{r=a} \frac{v}{1-v} \tag{27}$$

$$R_Y = \frac{h^s}{s!}\left(\frac{\partial^s Y}{\partial r^s}\right)_{r=a} \frac{v}{1-v} \tag{28}$$

and

$$R_Z = \frac{h^s}{(s+1)!}\left(\frac{\partial^s Z_n}{\partial r^s}\right)_{r=a} \left(\frac{1}{(1-v)^2} - 1 + \frac{sv}{1-v}\right) \tag{29}$$

Discussion—Ideally, when the Taylor series is used to extrapolate magnetic fields, the partial derivatives in the vertical direction are computed up to the order where the ratio of the successive terms of the Taylor series is nearly equal to h/a. Additional partials need not be computed, since the remaining terms of the series add to the remainder which is obtained by multiplying the highest-order computed term by a readily calculable numerical factor.

In extrapolating the geomagnetic field, more than six partials in the Taylor series would need to be computed before one could apply the limiting form of the remainder. (Vestine's spherical harmonic analysis showed that harmonics up to or beyond degree 6 are necessary to represent the

TABLE 1 – *Extrapolation of Z_n to height 100 km; intensity values in gammas*

Geographic colatitude	Geographic east longitude	Extrapolation by Taylor series				Extrapolation by spherical harmonics
		Value of terms in series			Total value by series of three terms	
		First term	Second term	Third term		
•	•					
30	300	−55,256	2489	−72	−52,839	−52,820
80	300	−25,918	1594	−47	−24,371	−24,340

TABLE 2 – *Extrapolation of Z_n to depth 100 km; intensity values in gammas*

Geographic colatitude	Geographic east longitude	Extrapolated value	
		By Taylor series of three terms	By spherical harmonics
•	•		
30	300	−57,817	−57,777
80	300	−27,559	−27,531

Earth's magnetic field.) However, for small extrapolation distances, that is, for $h/a \ll 1$, a smaller number of computed partials may suffice if the series converges rapidly. It will be instructive to make a comparison on this basis, since it is not attempted here to carry out a full-scale test of the remainder formulas.

Tables 1 and 2 show for two points the results of an extrapolation from the surface of the Earth. The component is Z_n as represented by the spherical harmonics computed by Vestine. The results indicate that for an extrapolation distance of 100 km the Taylor series converges rapidly.

In the downward extrapolation, the individual terms of the Taylor series are those used in an upward continuation with the exception that the second term of the downward series is negative. When only three terms of the series are used, the approximation of (23) is not valid; the two terms of (10) are approximately equal in the third term of the Taylor series. However, the remainder after three terms is small. In this example, it is the difference between the result obtained with the 48 spherical harmonics and that with the partial Taylor series.

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The Rate of Dissipation of Energy and the Energy Spectrum in a Low-Speed Turbulent Jet

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Abstract—This paper reports a study of the correlation coefficients between eddy velocity components measured at two different points in space, the energy spectrum, and the rate of dissipation of energy in a low-speed turbulent jet. The result of this study shows that the local isotropy proposed by Kolmogoroff prevails. It also gives the order of magnitude of the mean rate of dissipation of energy.

Introduction—Taylor [1935] related the rate of dissipation of energy for isotropic turbulence to the correlation coefficients between the velocity components measured at two different points in space. Later [*Taylor*, 1938a] he also related the energy spectrum for turbulence in general to the correlation coefficients. Since then there have been many experimental studies of the correlation coefficients, the energy spectrum and the rate of dissipation of energy in the wind tunnel and in the open air. This paper reports the results of another study along this line. The methods used to obtain these quantities are different from those used by most of other investigators and are designed to make maximum use of the data available.

In the wind tunnel, the air is confined to flow inside an enclosed boundary of uniform dimensions. The mean speed of the flow downstream is therefore a constant. In such a case, the distinction between the mean motion and the eddy motion is quite clear. The turbulence created by passing the flow through a grid was shown to be isotropic [*Taylor*, 1937, 1938b].

In the present study, the experiment was carried out in an enclosed room which was much larger than the field of motion. The field of motion was therefore subject to very little influence of the boundaries. In particular, the jet, after emerging from the pipe, was allowed to expand and to mix with the surrounding air freely. The mean speed of the flow changed in the downstream direction. Under such a circumstance, a clear-cut distinction between the mean motion and the eddy motion is not possible. The mean motion becomes a function of the way the motion is averaged. If a motion is considered to consist of eddies of many sizes, the larger the scale of average, the larger are the largest eddies that are excluded from the mean motion. Since an average over a volume of 20 × 20 × 20 cm in size was adopted to obtain the mean motion, the eddies considered in the present study are probably no larger than the size of the volume just mentioned.

Kolmogoroff [see, for example, *Batchelor*, 1947] had put forward a hypothesis that for any turbulence, local isotropy prevails at the small scale eddies when the Reynolds number is large. Evidence has already been presented that local isotropy does exist in atmospheric turbulence [*McCready*, 1953] and in turbulent flow studied in the laboratories [*Corrsin* and *Uberoi*, 1951; *Laufer*, 1951]. It is expected that local isotropy also exists at the small eddies in the present study, although the whole flow is certainly not isotropic. One of the main objects of present study was to test the existence of local isotropy in the flow. To this end the correlation function was studied and is reported below under *The correlation coefficient*, followed by *The energy spectrum* as a by-product. The other main object of this study was to determine the rate of dissipation of energy due to viscosity.

Description of the experiment—A stream of air produced by a blower, which regulated its speed, was sent through a section of pipe. While smoothing the flow, the pipe directed it into the field of observation. This field is 80 × 80 cm in the x-z plane and 40 cm in the y direction (the depth of field). The behavior of the jet in a steady state was investigated by introducing lint particles into the jet and studying the motions of the particles. No instruments, such as hot-wire anemometers, were used in this experiment to measure the air velocities in order to avoid the influence of the presence of the instruments on the flow. Figure 1 shows the coordinate system in relation to the jet.

The movement of the lint particles was recorded by two Crown Graphic 4 × 5-inch cameras, with f/4.7, 135 mm lenses, in a stereoscopic arrangement. The exposure time was approximately a half second or less. The particle velocities were determined by the spacing of periodic stroboscopic

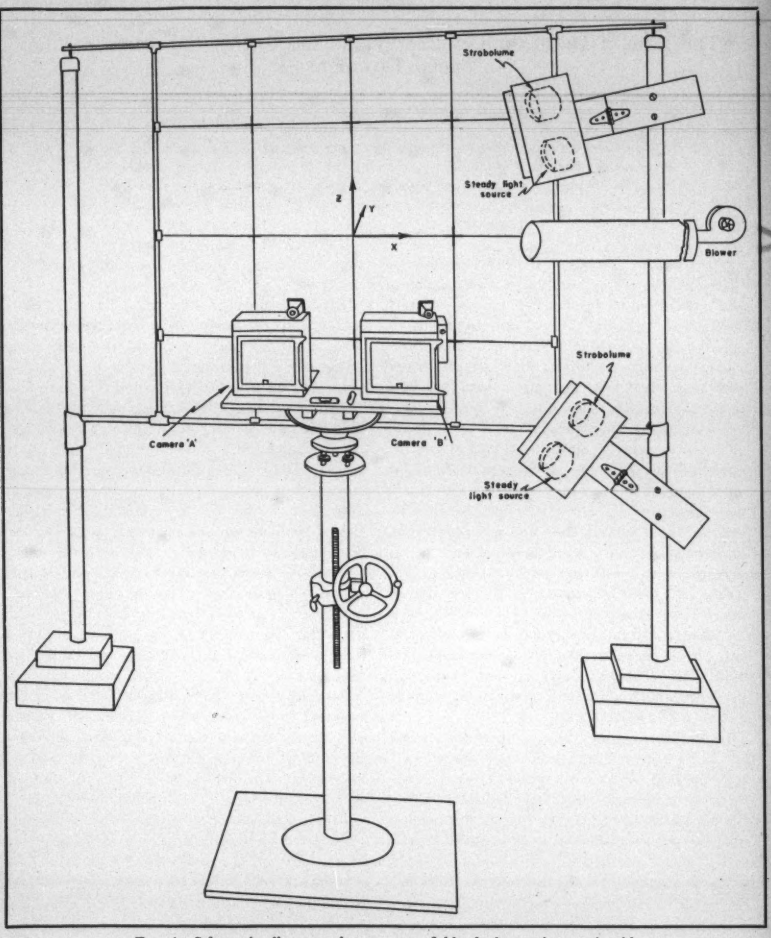

FIG. 1 – Schematic diagram of apparatus, field of observation, and grid

flashes which appeared as dots on the photographed particle tracks. The space position of the particle tracks on the photographs, relative to a fixed grid, were determined through geometric considerations [*Miller* and others, 1955].

The velocity components, u, v, and w, of a particle were assumed to be instantaneous values and were applied to the mid-point of the track. This procedure yielded a particle defined at a fixed point in space and moving at a speed given by its velocity components. The lint particles were assumed to travel with the air motions of the jet. The effects of the weight of the particles were considered and corrected for. For a more detailed

description of the experiment the reader is referred to the final report of the project [*Miller* and others, 1955].

In this study, the following experiments were carried out:

(1) One experiment, designated as Set VIII, blower speed 65, had a mean exit velocity of approximately 63 cm/sec. The exposure time of the photographs for this set was about a half second. For the sake of brevity, this set will hereafter simply be called Speed 65.

(2) Another experiment, designated as Set VIIIa, blower speed 65, was conducted under exactly the same conditions as the above set. But the exposure time of the photographs was about only a quarter of a second. With the particle tracks shortened in proportion to the exposure time, it was possible to introduce more lint particles into the field without making the photographs too cluttered and unreadable. Saturation of a field with lint particles, in turn, made it easy to choose pairs of particles that were close together. These close particles pairs, as will be seen later, are essential for the determination of the curvature of the correlation curve at the highest point of the curve. It was found later, however, that even from this set it was not possible to find enough close particle pairs for an accurate determination of the curvature desired. No further attempt was made to introduce even more lint particles into the field, for such an attempt required a further cut on the exposure time and would endanger the accuracy of the determination of the particle velocities. This set was therefore used in the same way as the above set and was sometimes freely incorporated into it. This set will hereafter be referred to as Speed 65a.

(3) Still another, designated as Set VIII, blower speed 58, had a mean exit velocity of approximately 50 cm/sec. The exposure time of the photographs for this set was about a half second. This set will hereafter be called Speed 58.

The field of motion—In order to define a mean velocity field which would include the three-dimensional characteristics of the jet, it was decided to average the particle data through 20 × 20 × 20-cm cubes. The cubes were chosen so that a cube overlapped each of its surrounding cubes by 10 cm (half the volume of the cube) [*Rib*, 1954].

The average velocity components, $\bar{u}$, $\bar{v}$, and $\bar{w}$, and the average space coordinates, $\bar{x}$, $\bar{y}$, and $\bar{z}$, of a volume were obtained by dividing 20 × 20 × 20-cm cube summations by the total number of particles in the volume. The average velocity components were assigned to $\bar{x}$, $\bar{y}$, $\bar{z}$, the particle-density centroid of the cube.

To represent the depth of field, five x-z planes at y = 6, 12, 18, 24, and 30 cm were chosen. The procedure used to obtain the values of the mean velocity components and mean space coordinates for use on the five planes, involved plotting graphs of $\bar{u}$, $\bar{v}$, $\bar{w}$, $\bar{x}$, and $\bar{z}$ against $\bar{y}$ for each parallelepiped defined by a 20 × 20-cm square on the x-z plane. The values to be plotted on the five planes were obtained from the parallelepiped graphs where y = 6, 12, 18, 24, and 30 cm intersected the $\bar{u}$, $\bar{v}$, $\bar{w}$, $\bar{x}$, and $\bar{z}$ curves.

Proceeding in this manner with all the parallelepipeds and drawing isopleths among the resulting values of the velocity components on each of the five planes, there was obtained a velocity distribution for the whole field of motion. Figure 2 illustrates the distribution of $\bar{u}$ and $\bar{v}$ at y = 18 cm.

The mean velocity at the position of a given particle was then obtained by locating its position on a plane. In a majority of cases the y coordinate of the particle fell between two planes. In these cases, $\bar{u}$ (or $\bar{v}$) was obtained by linear interpolation.

By means of Reynolds' definition of eddy velocities, $u' = u - \bar{u}$ and $v' = v - \bar{v}$, the u' and v' for each particle were obtained.

The correlation coefficients—The correlation coefficient between u_1' at one point and u_2' at another point, with the separation δx between the two points, is defined by

$$R_{u_1'u_2'} = \frac{\overline{u_1'u_2'} - \overline{u_1'}\,\overline{u_2'}}{\sqrt{\overline{u_1'^2} - \overline{u_1'}^2}\sqrt{\overline{u_2'^2} - \overline{u_2'}^2}} \qquad (1)$$

In the literature, it was found that the average, designated by the bar, usually means the average over time. This is the case when u_1' and u_2' are measured by two anemometers located at two fixed points. In the present case, however, the velocities may only be obtained for those positions in space that were occupied by the lint particles. Therefore, when pairs of particles were chosen for use in the $R_{u_1'u_2'}$ computations these particles may have come from any part of the field. The average over these pairs then has the characteristics of an average over space. When the pairs chosen from different photographs that were taken at different times are combined and averaged, it also has the characteristics of an average over time. It is evident that in the present case $R_{u_1'u_2'}$ is a function only of δx. The correlation coefficients between any two velocity components at two different points can be similarly defined.

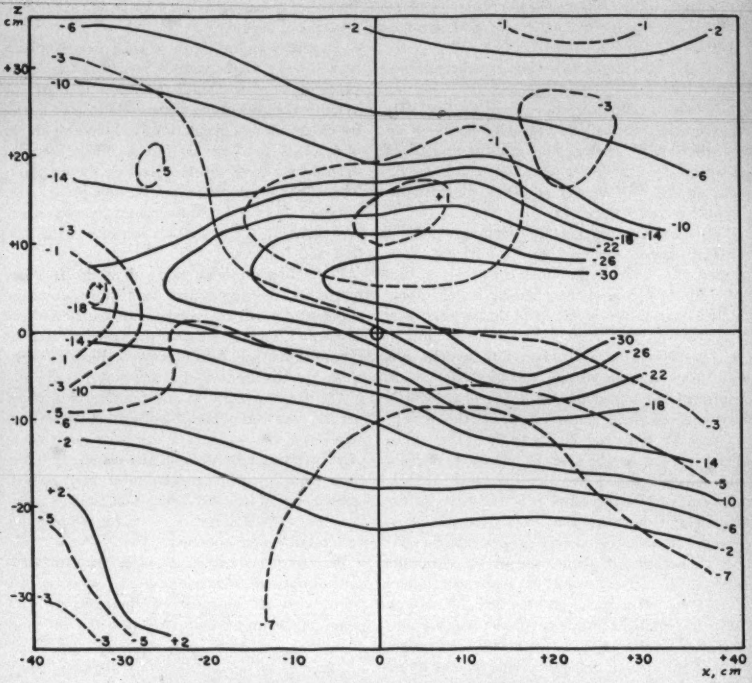

FIG. 2 - The $x - z$ plane at $y = 18$ cm showing the analyzed field of mean motion; the solid lines are the u component and the dashed lines are the $\bar{v}$ component, cm/sec

To study the variation of $R_{u_1'u_2'}$ with δx, two particles having similar y and z positions were taken as a pair. Since it is rare for the two members of a pair to have exactly the same y and z positions, some tolerance was allowed for these coordinates. When this procedure is followed, one finds many pairs with all different possible separations δx. These pairs were arranged in the ascending order of δx and divided into groups. For each group $R_{u_1'u_2'}$ was computed and plotted against the mean value of δx of that group.

$R_{u_1'u_2'}$, as an estimation of the true correlation coefficient between u_1' and u_2' at a distance δx apart, is subject to errors due to sampling, to the tolerance, and to the fact that in each group δx ranges over a certain interval instead of being held at a fixed value.

With the tolerance set at one cm in the y direction and two cm in the z direction for Speed 65a, and at three cm each for both the y and z directions for Speed 65, a total of 486 particle pairs was obtained from the combined data for the study of $R_{u_1'u_2'}$ as a function of δx. These pairs were divided into 13 groups of 35 pairs each and a fourteenth group of 31 pairs. $R_{u_1'u_2'}$ was computed for each group. Figure 3 shows the results.

To obtain $R_{v_1'v_2'}$ as a function of δx, some preliminary steps were necessary in order to eliminate the influence of a draft current coming from outside of the room through a small opening at the upper part of the window, because the tape used to seal the window was dried out and had cracked open. This was not discovered during the experiment because a black velvet background drape completely concealed the source of the draft. A study of the mean velocity charts shows that the

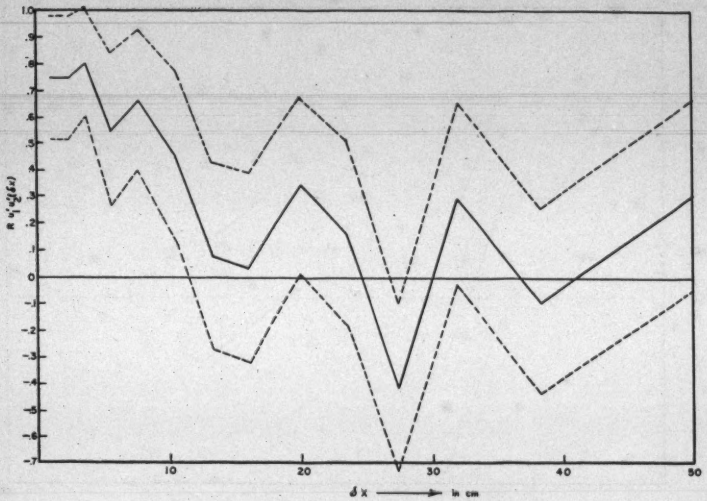

FIG. 3 – $R_{u_1' u_2'}(\delta x)$ for Speed 65 and Speed 65a

strength of the draft was weak compared to that of the jet and that the draft had a component only in the y direction. This insures that the draft did not affect the u component. The presence of this draft, however, makes it impossible to handle the v component correctly, for the draft may have been present in some photographs and not in others, and its strength may have varied from one to the other. The only way to study the v component is to select those photographs which do not show the presence of the draft.

Among the twelve photographs taken in the experiment Speed 65a, three were taken on July 1, 1953 and nine were taken on July 10, 1953. A study of the v component of those two groups shows that those taken on July 1 were definitely subject to the draft while those taken on July 10 were not. Only the latter group was used for the calculation of $R_{v_1' v_2'}$.

Without the presence of the draft v is expected to be quite small and random and thus itself may be taken as a good representation of the eddy motion in the y direction. (A rough estimate of the mean value of v from some of the photographs for a portion of the field gave a value very nearly equal to zero.) For this reason, and also as a time saving device, $R_{v_1 v_2}$ instead of $R_{v_1' v_2'}$ was studied.

With the tolerance set at one cm in the y and z directions, 229 particle pairs were obtained. According to the ascending order of δx, they were divided into ten groups, with the last group having one pair less than the other groups. $R_{v_1 v_2}$ was computed for each group and the results are shown in Figure 4.

The data for the experiment Speed 58 were treated in the same way as in the experiment Speed 65. For the study of $R_{u_1' u_2'}$ as a function of δx, the tolerance was set at three cm in the y and z directions. Four hundred twenty particle pairs were obtained and divided into 14 even groups with 30 pairs in each group. $R_{u_1' u_2'}$ was computed for each group. Figure 5 shows the results.

A similar study for $R_{u_1' u_2'}$ as a function of δz was made. Allowing a tolerance of three cm in the x and y directions, 300 particle pairs were obtained and divided into 12 groups of 25 pairs each. The results of these computations are shown in Figure 6.

As is expected from the sampling theory, all the correlation curves, Figure 3 to 6, show some fluctuations. As an indication of the significance of the computed correlation coefficients, the 95 pct confidence limits, obtained from the Student t formula, are computed and appear as the dashed lines in these figures.

Measurements in wind tunnels have shown that, except for that portion of the correlation curve

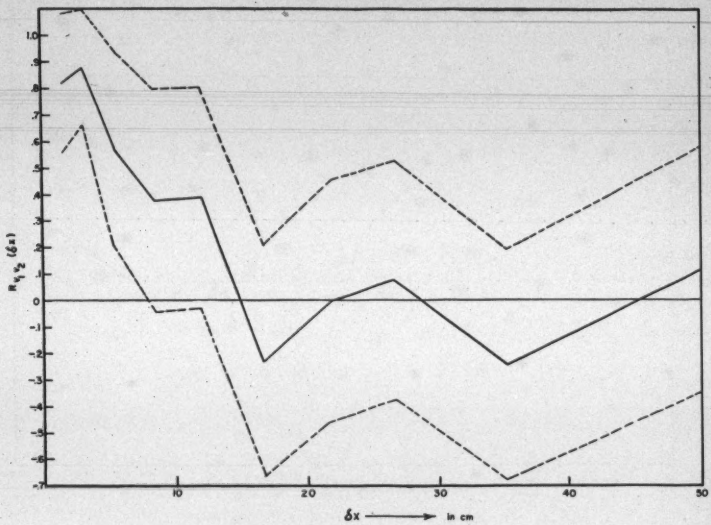

FIG. 4 – $R_{v_1v_2}(\delta x)$ for Speed 65a

very near to the origin (corresponding to zero separation), the shape of the correlation curve does not change with the speed of the mean flow. In the present case, because of the sampling fluctuations, it is not possible to assert whether the slope of the correlation function changes with the strength of the mean flow. It may be said, however, that when the 95 pct confidence limits of the computed correlation are considered, the present data do not contradict the above result found in wind tunnels.

Kolmogoroff's theory predicts that for the locally isotropic eddies in the inertial subrange, the correlation functions satisfy the 2/3 power law.

(Kolmogoroff's theory actually predicts a 2/3 power law and a relationship like (5) for the mean square of the velocity difference between two points; that is, for $\overline{(u_1' - u_2')^2}$. The characteristics of this quantity are slightly different from $R_{u_1'u_2'}$, when the mean value of u' is not exactly zero, as is the case in this study. The difference, however, was found to be quite small. It serves our purpose just as well to use (2) to (5).) That is, in the present case

$$R_{u_1'u_2'}(\delta x) = 1 - c_1(\delta x)^{2/3} \tag{2}$$

$$R_{u_1'u_2'}(\delta z) = 1 - c_2(\delta z)^{2/3} \tag{3}$$

$$R_{v_1v_2}(\delta x) = 1 - c_2(\delta x)^{2/3} \tag{4}$$

It also predicts that for this same subrange

$$R_{u_1'u_2'}(\delta z) = R_{u_1'u_2'}(\delta x)\,\frac{(\delta x)}{2}\,\frac{\partial R_{u_1'u_2'}(\delta x)}{\partial(\delta x)} \tag{5}$$

From (2), (3), and (5), it is found that the following relationship

$$c_2 = \frac{4}{3}\,c_1 \tag{6}$$

may be used to replace (5).

From (2), it is found that

$$\log c_1 = \log\,[1 - R_{u_1'u_2'}(\delta x)] - \frac{2}{3}\log\,(\delta x) \tag{7}$$

Therefore, if $1 - R_{u_1'u_2'}\,(\delta x)$ is plotted against δx on a log-log scale, the points should follow a 2/3 slope if the eddies are in the inertial subrange. This same statement applies equally well to the other correlation coefficients.

For the four cases of R studied, $1 - R$ was plotted against the argument of R on a log-log scale. They are shown by Figures 7 to 10. It is seen from these graphs that in general the points do follow a 2/3 slope. As it is not expected that the eddies of very large scale should fall into this inertial subrange, an inspection of the points plotted shows that the points beyond $\overline{\delta x}$ (or δz)

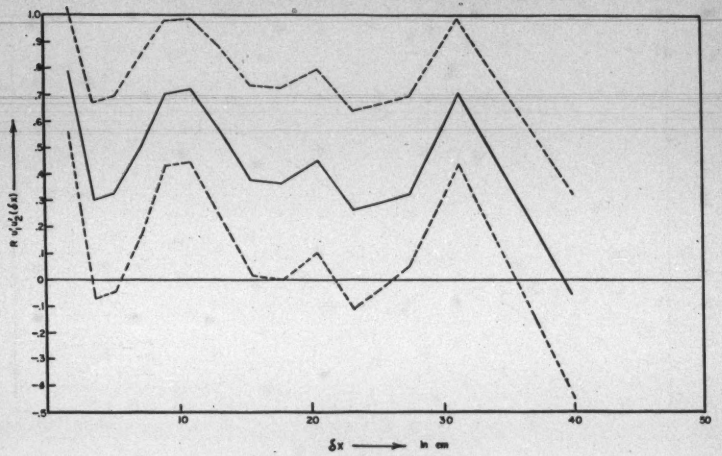

FIG. 5 – $R_{u_1' u_2'}(\delta x)$ for Speed 58

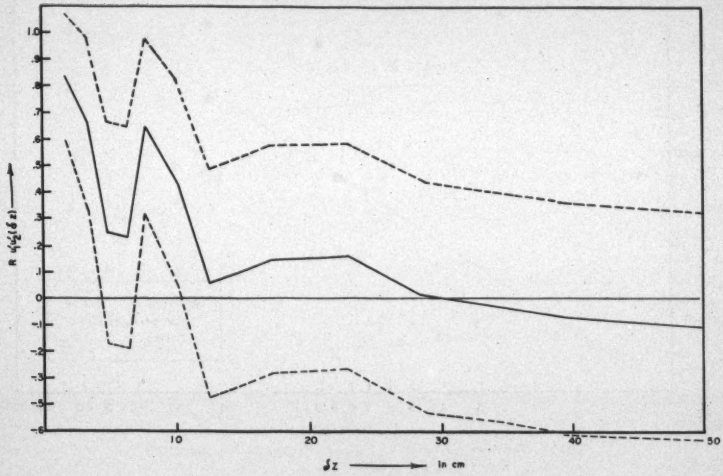

FIG. 6 – $R_{u_1' u_2'}(\delta z)$ for Speed 58

equal to 30 cm tend to follow a different slope. Thus the points beyond 30 cm were arbitrarily excluded. The other points were used to determine the constants c_1 and c_2 in (2) to (4) by means of the least-squares method. The results are given by Table 1.

It is seen that for the experiment Speed 58 the relationship between c_1 and c_2, as given by (6), is satisfied. For Speed 65, it is not satisfied. This may be due to the fact that in this case $R_{v_1 v_2}(\delta x)$ is used instead of $R_{u_1' u_2'}(\delta x)$. Some mean motion which is not isotropic may be included in v. This,

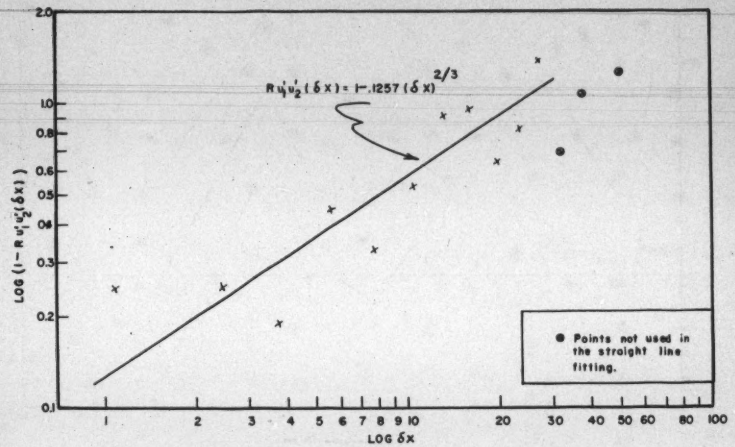

FIG. 7 – Relation of log $[1 - R_{u_1'u_2'}(\delta x)]$ to log δx for Speed 65 and Speed 65a

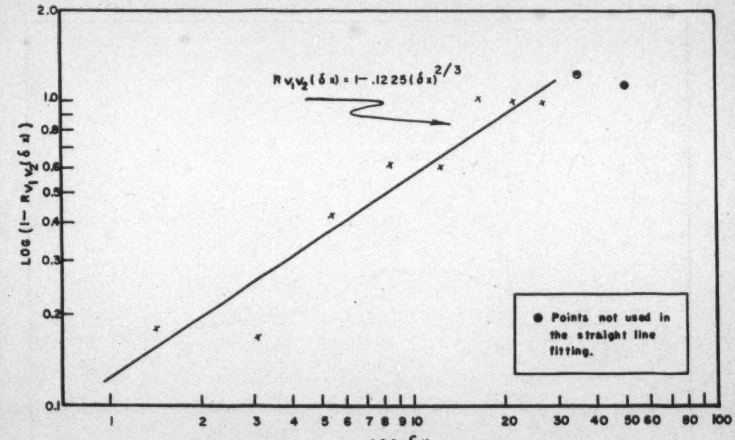

FIG. 8 – Relation of log $[1 - R_{v_1v_2}(\delta x)]$ to log δx for Speed 65a

of course, would make the comparison of c_1 and c_2 in this case less meaningful.

As a whole, judging from the general tendency for the points to follow a 2/3 slope and from the fact that (6) is satisfied for Speed 58, it is concluded that the local isotropy does prevail in these experiments.

The energy spectrum—The energy spectrum concerns the distribution of energy with wave numbers (or frequencies) of the motion. If $F(k)\,dk$ is the fraction of u'^2 (or v'^2) contained in a range of wave numbers from k to $k + dk$, where k is the number of waves per unit length, then

$$F(k) = 4\int_0^\infty R_{u_1'u_2'}(\delta x)\cos 2\pi k(\delta x)\,d(\delta x) \qquad (8)$$

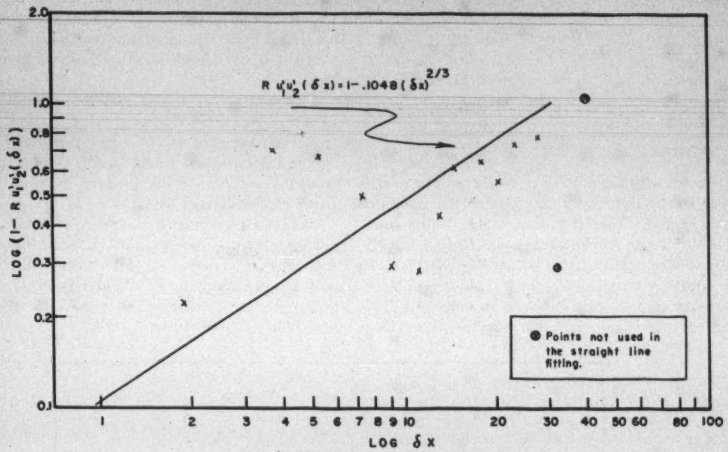

FIG. 9 – Relation of log $[1 - R_{u_1' u_2'}(\delta x)]$ to log δx for Speed 58

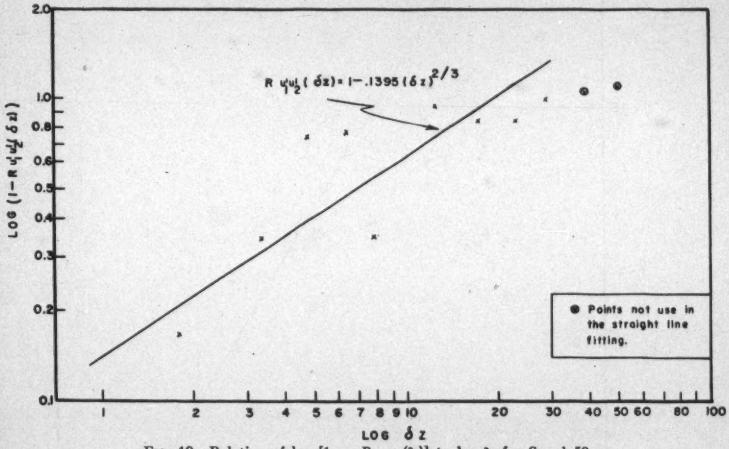

FIG. 10 – Relation of log $[1 - R_{u_1' u_2'}(\delta z)]$ to log δz for Speed 58

and

$$\int_0^\infty F(k)\, dk = 1 \tag{9}$$

A reverse transform also exists between $R_{u_1' u_2'}(\delta x)$ and $F(k)$. Therefore, if one is known, the other can be determined by the Fourier transform. In the present case, the energy spectrum is estimated from the computed correlation coefficients.

To obtain $F(k)$ from a given $R_{u_1' u_2'}(\delta x)$, Eq. (8) is usually replaced by a partial sum so that

$$F(k) = 4 \sum_{i=0}^{n} R_{u_1' u_2'}(\delta x)_i \cos 2\pi k (\delta x)_i \cdot [(\delta x)_{i+\frac{1}{2}} - (\delta x)_{i-\frac{1}{2}}] \tag{10}$$

It is apparent that (10) is an approximation of (8) and that the accuracy of this approximation in-

TABLE 1 – *The constants c_1 and c_2 determined by the least-squares method*

Speed 65 and Speed 65a	$c_1 = 0.1257\ \text{cm}^{-2/3}$ $c_2 = 0.1225\ \text{cm}^{-2/3}$
Speed 58	$c_1 = 0.1048\ \text{cm}^{-2/3}$ $c_2 = 0.1395\ \text{cm}^{-2/3}$

creases with the number n. In the present case, it also depends on the accuracy of the computed $R_{u_1' u_2'}(\delta x)$. From (10), one is able to determine $F(k)$ for any k, while *Tukey* and *Hamming* [1949] have shown that actually, when $R_{u_1' u_2'}(\delta x)$ is given only at a certain interval of δx, it is possible to determine $F(k)$ only for a certain range of k. This range of k is automatically provided when Tukey and Hamming's method for obtaining the energy spectrum from the correlation coefficient is followed. For this reason, their method will be used here.

Following Tukey and Hamming's method, the values of $R_{u_1' u_2'}(\delta x)$ of Speed 65, from $\delta x = 0$ to $\delta x = 30$ cm were read off at every two cm from Figure 3. From these values of $R_{u_1' u_2'}$, $F(k)$ was computed according to the formulas given in their paper previously mentioned.

The same procedures were applied to obtain the energy spectrum from $R_{v_1 v_2}(\delta x)$ for Speed 65, and from $R_{v_1' v_2'}(\delta x)$ and $R_{v_1' v_2'}(\delta z)$ for Speed 58. The only exception was that for Speed 58, $R_{u_1' u_2'}(\delta x)$ was read every two cm of δx up to $\delta x = 40$ cm instead of up to $\delta x = 30$ cm. Also, to correspond

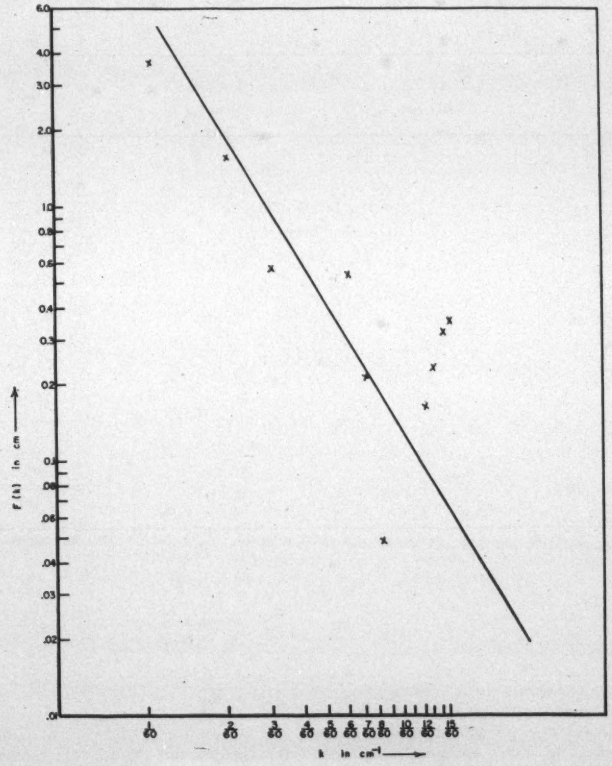

FIG. 11 – F(k) for Speed 65 and Speed 65a

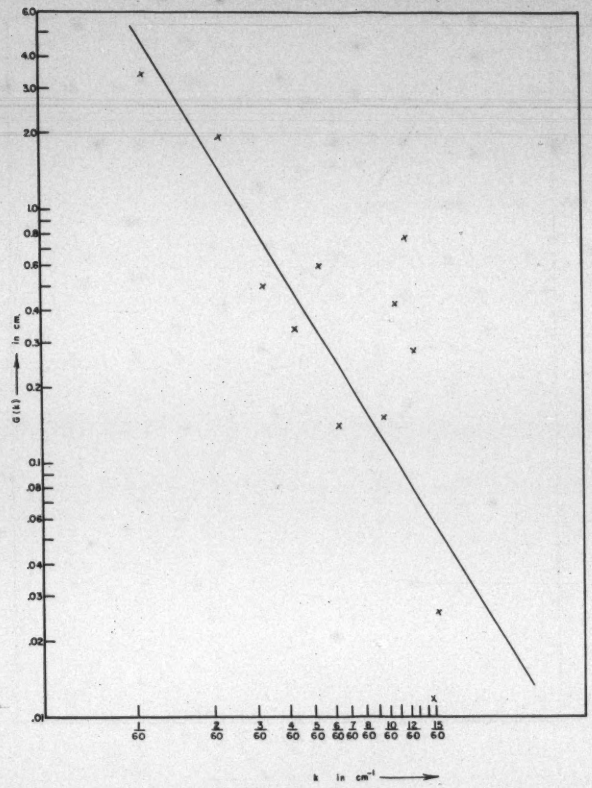

FIG. 12 – G(k) for Speed 65a

with the convention, the energy spectrum obtained from the transverse correlation coefficient; that is, $R_{v_1v_2}(\delta x)$ or $R_{u_1'u_2'}(\delta z)$, is designated as $G(k)$.

The results of these computations show that there are some small negative values of $F(k)$ and $G(k)$. In reality, $F(k)$ or $G(k)$ should never be negative. Such negative values are the results of sampling errors in the correlation coefficients. Their presence means only that there is a certain small inaccuracy in the computation but it in no way impairs the general correctness of the results. In fact, these negative values may be eliminated altogether if the 'pre-whitening' process designed by Tukey is applied to the computation. (The 'pre-whitening' process was brought to the writers' attention by the reviewers of this paper.)

The values of $F(k)$ and $G(k)$ are plotted against k on a log-log scale in Figures 11 to 14. The few negative values of course do not appear in these diagrams. The solid line in each diagram represents the $-5/3$ law between $F(k)$ $(G(k))$ and k from the similarity theory. The solid line in all cases appears to fit the data well. Again this suggests that the eddies in these experiments belong to the inertial subrange of the similarity theory.

The dissipation of energy—For isotropic turbulence, *Taylor* [1935] has shown that the mean rate of dissipation of energy per unit mass $\overline{W}$ by the viscosity is given by

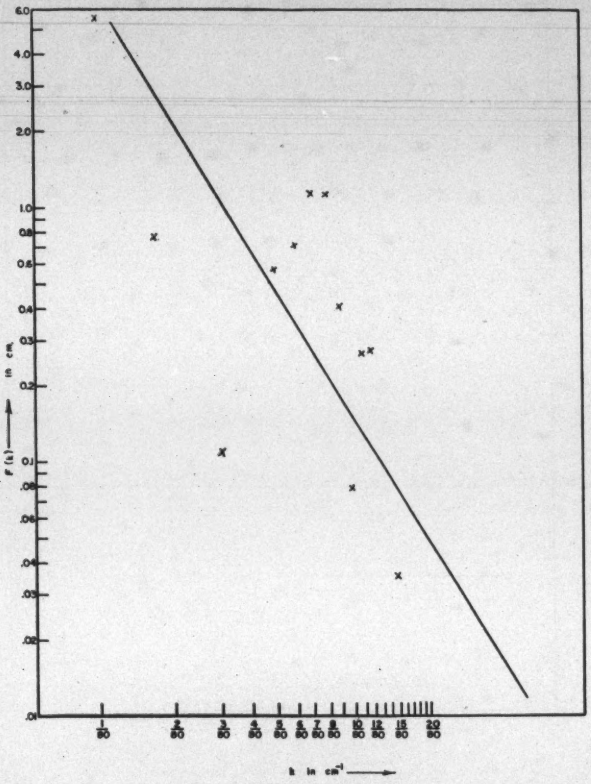

FIG. 13 – F(k) for Speed 58

$$\overline{W} = 15\nu\overline{\left(\frac{\partial u'}{\partial x}\right)^2} \tag{11}$$

If a length λ, the so-called microscale of the turbulence, is defined as

$$\frac{1}{\lambda^2} = 2 \operatorname*{Lim}_{\delta x \to 0} \frac{1 - R_{u_1' u_2'}(\delta x)}{(\delta x)^2} \tag{12}$$

then, as shown by Taylor, λ relates to $\overline{W}$ through

$$\overline{W} = 15\nu \frac{\overline{u'^2}}{\lambda^2} \tag{13}$$

Previous investigators of turbulence usually determined λ from the curvature of the correlation curve at the highest point of the curve (corresponding to zero separation between the two members of a pair). Then by means of (12) and (13) they determined $\overline{W}$. In the present study, $\overline{W}$ was directly determined from (11). $\overline{(\partial u'/\partial x)^2}$ was obtained by finding the limiting value of $\overline{(\delta u'/\delta x)^2}$ as δx approaches zero.

The same particle pairs used for the computation of the correlation coefficient $R_{u_1' u_2'}(\delta x)$ for Speed 65 and Speed 65a were used for this study. Since the quantity $\overline{(\delta u'/\delta x)^2}$ is now considered, the effect of the tolerance on this quantity becomes important when δx is small and must be corrected for.

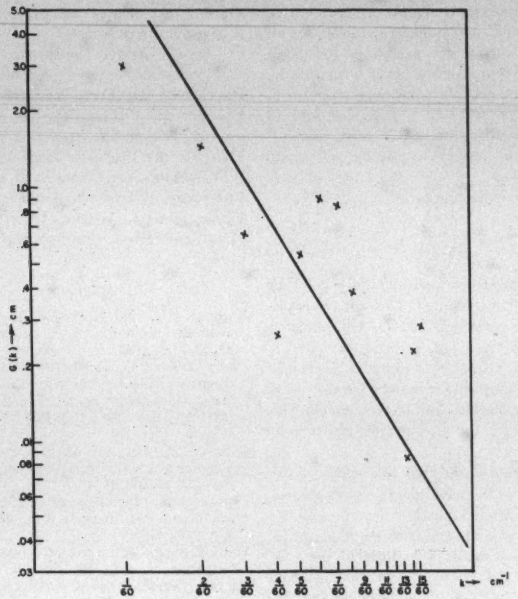

FIG. 14 – G(k) for Speed 58

In allowing a tolerance

$$\overline{\left(\frac{\delta u' + r\dfrac{\partial u'}{\partial r}}{\delta x}\right)^2}$$

is actually obtained instead of $\overline{(\delta u'/\delta x)^2}$, where $r^2 = (\delta y)^2 + (\delta z)^2$. Expanding

$$\overline{\left(\frac{\delta u' + r\dfrac{\partial u'}{\partial r}}{\delta x}\right)^2} = \overline{\left(\frac{\delta u'}{\delta x}\right)^2} + 2\overline{\left(\frac{r}{\delta x}\frac{\partial u'}{\partial r}\frac{\delta u'}{\delta x}\right)} + \overline{\frac{r^2}{(\delta x)^2}\left(\frac{\partial u'}{\partial r}\right)^2}$$

As there is no reason to believe that the sign of the two gradients

$$\frac{\partial u'}{\partial r} \quad \text{and} \quad \frac{\delta u'}{\delta x} \quad \text{in} \quad \frac{r}{\delta x}\frac{\partial u'}{\partial r}\frac{\delta u'}{\delta x}$$

are correlated, in the mean the term is assumed to vanish. The second assumption that was made was

$$\overline{\frac{r^2}{(\delta x)^2}\left(\frac{\partial u'}{\partial r}\right)^2} \simeq \overline{\left(\frac{r^2}{(\delta x)^2}\right)}\,\overline{\left(\frac{\partial u'}{\partial r}\right)^2}$$

Assuming $\overline{(\partial u'/\partial r)^2}$ is of the same order of magnitude as $\overline{(\delta u'/\delta x)^2}$ it follows that

$$\overline{\left(\frac{\delta u' + r\dfrac{\partial u'}{\partial r}}{\delta x}\right)^2} \simeq \left[1 + \overline{\left(\frac{r^2}{(\delta x)^2}\right)}\right]\overline{\left(\frac{\delta u'}{\delta x}\right)^2}$$

At large values of δx the correction is negligible. However, it becomes very important at small values of δx.

TABLE 2 – *Summary of* $\overline{(\partial u'/\partial x)^2}$ *and* $\overline{W}$

	$\overline{(\partial u'/\partial x)^2}$	$\overline{W}$	95 pct confidence limit of $\overline{W}$
	sec^{-2}	ergs/gm sec	
Speed 65 and Speed 65a.....	0.82	1.84	0.85–3.96
Speed 58.....	1.44	3.24	1.35–7.70

To further reduce the chances of errors appearing in the values of $\delta u'$, as a result of the tolerance, all particle pairs with r^2 one magnitude (or more) greater than $(\delta x)^2$ were rejected from further study.

The remaining particle pairs were arranged in the ascending order of δx and divided into 13 groups, each group containing 35 pairs. $(\delta u'/\delta x)^2$ for each pair and $\overline{(\delta u'/\delta x)^2}$ and $\overline{\delta x}$ for each group were then obtained.

To obtain the correction factor

$$1 + \left(\frac{r^2}{(\delta x)^2}\right)$$

$r^2/(\delta x)^2$ for each particle pair and $\overline{r^2/(\delta x)^2}$ for all of the groups were computed. Through the application of these correction factors, the corrected values of $\overline{(\delta u'/\delta x)^2}$ were obtained.

The data for Speed 58, treated in a manner similar to that described for Speed 65, consisted of 420 particle pairs divided into 14 even groups. The corrected $\overline{(\delta u'/\delta x)^2}$ and $\overline{\delta x}$ for each group were computed.

In order to obtain $\overline{(\partial u'/\partial x)^2}$ the values of the corrected $\overline{(\delta u'/\delta x)^2}$ in each of the two cases studied were plotted on a semilogarithm diagram with log $\overline{(\delta u'/\delta x)^2}$ as the ordinate and $\overline{\delta x}$ as the abscissa. In each diagram a parabola was fitted to the first few points at small $\overline{\delta x}$ by the method of least squares. The intersection of the ordinate and the line fitted determines the values of $\overline{(\partial u'/\partial x)^2}$. The reason for fitting the points by a parabola is explained in the Appendix of a progress report by *Chiu* and *Rib* [1955].

The values of $\overline{(\partial u'/\partial x)^2}$ and $\overline{W}$ obtained for the above two cases are summarized in Table 2. The confidence limits were obtained by the consideration of the Student t method. It is seen from this table that the rate of dissipation determined for Speed 58 is slightly larger than that for Speed 65. This does not agree with the results found in the wind tunnels where the rate of the dissipation increases with increasing mean flow. But when the confidence limits are taken into consideration, it is seen that there is a chance that the true rate of dissipation of energy can still be larger for Speed 65 than that for Speed 58. That the computed $\overline{W}$ is larger for the smaller mean flow here is probably a result of the sampling fluctuations. However, their agreement in order of magnitude suggests that at least, the order of magnitude of $\overline{W}$ given above is correct.

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A Portable Tsunami Recorder*

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Abstract—A compact self-contained long-period wave recorder has been developed for remote operation on small islands where the influence of continental land masses is minimized. The instrument can be installed in two or three days, requires no electric power, and needs only weekly attention. It can detect waves less than one cm high at its period of maximum response (1000 sec), and it attenuates both swell and tides to about three per cent of their relative amplitudes.

Introduction—From its first installation in 1948 the tsunami recorder on the Scripps Institution pier has exhibited pronounced wave activity over much of the spectrum intermediate between the swell and the tides [*Munk*, *Iglesias*, and *Folsom*, 1948]. However, only in the case of a large tsunami [*Munk*, 1953] has convincing coherence been found between the records obtained from this instrument and a similar installation at Oceanside (20 mi N of Scripps), save that both records reflect the same general signal amplitudes from day to day. That much of this activity may be locally generated has been suggested by *Munk* [1949] and *Isaacs*, *Williams*, and *Eckart* [1951], who show that once generated, it can be effectively 'trapped' as waves rebounding along the coast. Such energy as may leak off into deep water would have its already small amplitudes greatly reduced. On the other hand, according to *Cochrane* and *Arthur* [1948], most of the energy of tsunamis approaching the California coast is reflected back out to sea.

It thus appears as if the continental shelf is a poor place to study tsunamis, and that the signal-to-noise ratio might be improved by making long-period wave measurements in deep water, or on small relatively isolated islands.

While no successful deep-ocean recorder has yet been developed, this paper describes a tsunami recorder specifically designed to be transported by air to such remote islands, where it can be installed by two or three men without outside assistance and operated on a semi-permanent basis with no more attention than an ordinary tide gage. Up to the present time eight temporary installations have been operated intermittently for a total of twenty months on six Pacific islands, and it is hoped to have at least two stations operating continuously in the Pacific in the near future.

Description of the instrument—A schematic of a typical installation of the tsunami recorder is shown in Figure 1. It consists of a tripod-mounted wave filter in a protected location, connected hydraulically to the sea by a tube or pipe, and electrically to the shore recorder by a three-wire cable. No external electric power is required. The distance between the respective elements can be as great as 1000 ft, which gives considerable latitude in the choice of instrument location. While the tripod is usually constructed at the site, the remaining components are packed for shipment in a suitcase-size wooden box equipped with a plastic cover, which can serve as an all-weather shelter for the recorder.

The tube installation—The tube from the wave filter to deep water essentially places the filter in the position of being able to receive offshore signals without appreciable distortion or attenuation and still occupy a site protected from waves and surf, and available for easy maintenance.

During early experiments with these recorders no tube was used, but it was soon evident that such protected locations abound with locally generated seiches having periods within the pass band of the filter and amplitudes much larger than the signals being sought. In fact, tsunamis themselves usually excite any local resonant water masses in a way which completely masks the character of the incoming signal.

The tube used in previous installations was a half inch inside diameter, transparent, vinyl-plastic garden hose, available in continuous lengths. The depth of the free end below sea level is not critical except that air bubbles, suspended sediment, and regions where currents can produce sustained dynamic pressures should be avoided. The tube is terminated at its outer end in a screened basket to prevent ingress of organisms or material likely to obstruct the flow of water. It was found necessary to tie the hose down every three feet or so in the surf zone, which requirement somewhat taxes the ingenuity of the field

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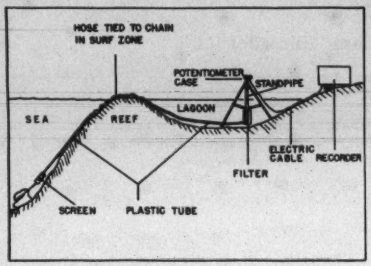

FIG. 1 – A typical tsunami recorder installation

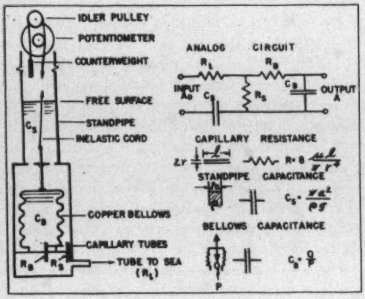

FIG. 2 – The wave filter and its electrical analog circuit

party. A scrap length of heavy chain makes excellent ballast, whereas coral boulders are very poor, tending to roll and pinch the tube.

The wave filter—Discrimination against unwanted signals is accomplished by the wave filter (Fig. 2). It consists of two capillaries, a copper bellows, and a standpipe arranged to form an hydraulic resistance–capacitance network as shown in the accompanying electrical analog circuit, the response characteristics of which are discussed below. Physically, the filter is a small brass canister with a removable bottom on which are mounted the copper bellows and glass capillary tubes. The canister is screwed on the lower end of a standpipe rigidly constrained to the vertical by any convenient means. The standpipe length is arbitrary save that its upper and lower ends must be respectively above and below the greatest anticipated sea level excursion. Pressure signals conducted to the filter by the hose result in vertical motions of the bellows which are converted into electrical signals by an inextensible cord passing up the standpipe around the shaft of a potentiometer, over an idler pulley, and down to a counter

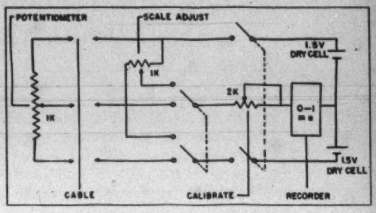

FIG. 3 – The wiring diagram for the recorder

weight. The potentiometer is in a sealed case with a supply of desiccant to remove any slight amount of moisture coming in around the shaft seal. (One can, alternatively, where electric power is available, measure the pressure difference across the bellows with a suitable transducer, and connect its output directly to a recording potentiometer.)

The recorder—A three-conductor cable connects the potentiometer to the control panel in the recorder case, which can be located ashore in any convenient spot. The simple bridge circuit (Fig. 3) employs four flashlight batteries in series parallel, which have a service life of about six months. Provision is made for applying a standardizing *calibrate* signal and adjusting the sensitivity to compensate for the gradual reduction in battery voltage. The Esterline Angus 0-1 ma, spring wound, strip chart recorder is manually set to center-zero. A chart speed of three inches per hour is adequate to resolve any signals that get through the filter.

Response characteristics—The amplitude response A, of the electric analog circuit (Fig. 2) to an incoming sinusoidal wave of unit amplitude A_0, as obtained by simple network theory is

$$\frac{A}{A_0} = \left[\left(1 + \frac{C_B}{C_S} + \frac{C_B}{C_S}\cdot\frac{R_B}{R_S}\right)^2 + \frac{C_B}{C_S}\cdot\frac{R_B}{R_S}\left(\frac{T'}{T} - \frac{T}{T'}\right)^2\right]^{-\frac{1}{2}} \quad (1)$$

where T is the period of the incoming wave and T' the period at maximum response, defined by

$$T' = 2\pi(R_B R_S C_B C_S)^{\frac{1}{2}} \quad (2)$$

The response function (1) is plotted in Figure 4 for the case $R_B/R_S = C_B/C_S = 1$. As with all single-stage RC filters, the amplitude response for periods long or short compared to T' falls off directly as $1/T$ or T respectively. But much can be done to control the shape of the curve (frequency cutoff) in the region $0.01 < T/T' <$

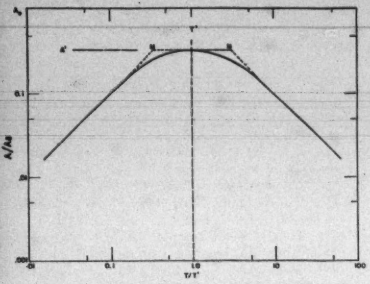

FIG. 4 – A typical amplitude response curve for the wave filter, where $R_B/R_S = C_B/C_S = 1$

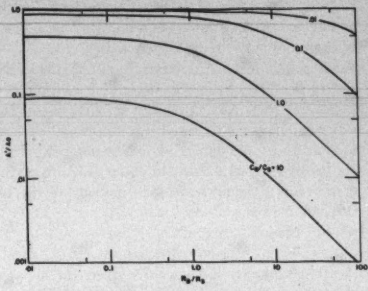

FIG. 6 – Maximum amplitude A' as a function of the resistance ratio, for four capacitance ratios

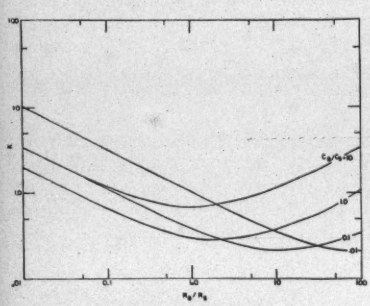

FIG. 5 – Band width K as function of the resistance ratio, for four capacitance ratios

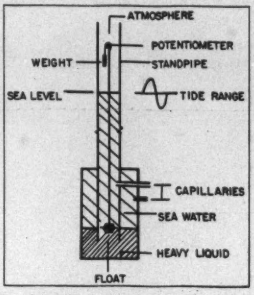

FIG. 7 – Schematic of new filter design eliminating bellows

100. If we define an *effective band width* K as that portion of the period spectrum between the intercepts at M and N (Fig. 4), K can be determined from (1) by equating the two terms on the right; namely

$$K = \frac{T'}{T} - \frac{T}{T'} = \frac{C_S}{C_B} \cdot \frac{R_S}{R_B} \left(1 + \frac{C_B}{C_S} + \frac{C_B}{C_S} \cdot \frac{R_B}{R_S}\right) \quad (3)$$

In addition the maximum amplitude A' occurs when $T = T'$

$$A' = A_0 \left(1 + \frac{C_B}{C_S} + \frac{C_B}{C_S} \cdot \frac{R_B}{R_S}\right)^{-\frac{1}{2}} \quad (4)$$

In Figures 5 and 6 K and A' are plotted against the resistance ratio R_B/R_S for various capacitance ratios C_B/C_S, and one can see by inspection how the performance of the filter varies as the circuit components are changed. It should be kept in mind that the *amplitude* discussed above refers to the pressure difference across the copper bellows. For a specific bellows the extension per unit pressure will determine the stroke available to operate a recording device.

The fluid resistance offered by the tube between the filter and the sea, shown in Figure 2 as R_t, is in series with the filter input impedance Z_f; it will reduce the amplitude response directly as the ratio R_t/Z_f. This attenuation is only important in the pass band where reactance is small, and it is sufficient to require that:

$$R_t \leq 0.1 \left[\frac{R_B \cdot R_S}{R_B + R_S}\right] \quad (5)$$

to obtain a practical compromise in component sizes without serious signal loss. Likewise, spurious signals generated along the tube by pressure changes elsewhere than at the free end are dissipated by movement of water through the seaward end of the tube before they can produce significant variations within the bellows.

Discussion—Present limited experience with island installations indicates that the long-period background noise in the open sea is very low—substantially less than one cm high. All tsunamis recorded to date have been only a few centimeters high, and they pass unnoticed on tide gages. In order to resolve such small signals present design modifications are aimed at improving the sensitivity from about 0.5 cm to about 0.5 mm wave height. Since the instrument is virtually temperature insensitive and does not respond to atmospheric pressure fluctuations, its resolution is principally governed by mechanical hysteresis in the potentiometer linkage. Moreover, the copper bellows is intrinsically a non-linear capacitance, and can itself be eliminated by substitution of a heavy liquid in the same standpipe, as shown in Figure 7. Such an improved instrument is currently undergoing tests.

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Chlorinity Titration

I. Evaluation of Potentiometric Errors

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Abstract—Various methods for potentiometric determination of the endpoint of a titration are discussed and sources of error considered. In the routine determination of salinities for dynamic-height computation using a commercial Ag indicating electrode and Ag-AgCl reference electrode, the equivalence point potential should first be determined with an accuracy of ten mv and the meter set to this value. The procedure of Knudsen is then followed and all samples and standards titrated to within five mv of the established endpoint potential.

Introduction—In the titration of halides in sea water with silver nitrate, the *Mohr* [1856] titration has generally been used with details of procedure and the analysis of data carried out by the method of Knudson [*Oxner*, 1946]. With the introduction of the vacuum tube millivoltmeter, an instrumental method of determining the titration endpoint became available [*Goode*, 1922]. This paper is the report of an examination of the potentiometric endpoint for sources of error. Electrode and sampling problems will be discussed in subsequent publications.

Equivalence point from data analysis—The theoretical plot of potential E against volume V for titration of chlorides with silver nitrate is a sigmoid curve [*Kolthoff* and *Furman*, 1931, p. 12; *Lingane*, 1953, p. 71], the first derivative curve is a symmetrical cusp or bell shape, and the second derivative curve is symmetrical and passes through zero. Figure 1 shows these curves, which can often be rather closely approximated in practice (see Fig. 2). The height, and to some extent the shape, of the curves will be influenced by the concentrations of the $AgNO_3$ solution and of the sample. This effect is discussed by *Kolthoff* and *Furman* [1931, pp. 11–15] but need not concern the present treatment since these concentrations vary only slightly between titrations in the Knudsen method. The volume scale of Figure 2 is compressed five times from that of Figure 1, and the derivative curves are much broader, presumably because equilibrium is slowly attained. The endpoint is sharp and reproducible, however, occurring at 127 mv, 18.36 ‰. The position of the E curve along the vertical axis will depend on the potential of the reference electrode that is used and may vary as the indicating electrode ages (see below). This variation of potential of the indicating electrode is currently being investigated.

The equivalence point is the steepest portion of the E vs V curve, and the curve should be symmetrical about this point. As shown by the vertical dashed line in Figures 1, 2, and 3, the equivalence point is also the maximum of the first derivative curve ($\Delta E/\Delta V$ vs V), or the zero intercept of the second derivative curve ($\Delta^2 E/\Delta V^2$ vs V). *Lingane* [1953, p. 70] shows how the equivalence point may be found numerically from calculated values of the second derivative. These methods will be discussed in succeeding paragraphs.

Actual titration data may not give a perfect sigmoid curve when plotted. With careful work, highly reproducible results may be obtained as shown in Figure 2, and *Furman* [1930] cites papers reporting five or six place accuracy in the potentiometric titration of halides with silver nitrate. For routine dynamic calculations, salinity must be determined with an accuracy of ±0.02‰ [*Sverdrup* and others, 1942, p. 54]. To obtain this accuracy the precautions listed by *Oxner* [1946] should be followed and the electrodes kept clear of silver chloride curds. Efficient stirring is absolutely essential.

Graphical Analysis—To determine the electrode potential at the equivalence point, standard sea water need not be used. A rapid titration should first be made with ordinary sea water to get an approximate value for this potential. Two or more titrations are then run with the same sea water. The electrode potential should be recorded after each 0.02‰ addition of silver nitrate near the equivalence point. (The double milliliter, per mille chlorinity unit on the Knudsen burette, will be represented by the symbol ‰ in this paper.)

The potential values in Table 1 were taken from the analyst's files of titration data for determination of the endpoint potential. The solid line of Figure 2 is the E vs V plot of the data from these three titrations. The endpoint of the titration was selected by inspection of the curve as 124 mv, 18.36‰. The data from replicate titrations do not always fall so closely on one curve, but the end

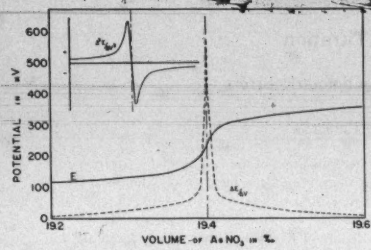

FIG. 1 – Calculated curves for the potentiometric titration of standard sea water with silver nitrate; E, titration curve based on the Nernst equation ($E = E_0 - 0.059 \log [Ag^+]$); $\Delta E/\Delta V$, first derivative curve; $\Delta^2E/\Delta V^2$, second derivative curve

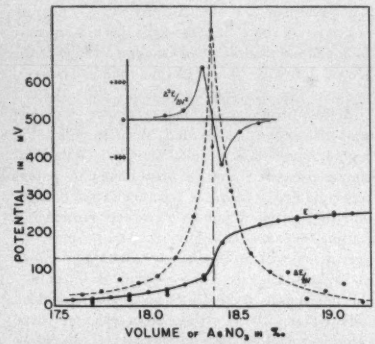

FIG. 2 – Curves for the potentiometric titration of a sub-standard sea-water with silver nitrate; Ag indicating electrode, Ag-AgCl reference electrode with saturated Na_2SO_4 bridge; the data for the three replicates are given in Table 1

point potentials usually agree within a few millivolts and the volumes within 0.01‰. The dashed curve is the plot of the numerical values of $\Delta E/\Delta V$ vs V. The $\Delta^2E/\Delta V^2$ vs V plot is shown by the insert. The endpoint from the derivative curves is found to be at 127 mv, 18.36‰.

Additional data were collected near the endpoint for titrations C and B but are not listed in Table 1. These were plotted and smooth S curves drawn, E of Figure 3. The equivalence point for each titration may now be estimated by inspection, or with the aid of derivative plots constructed as follows. The potential change for each volume increment ΔV of 0.01‰ is estimated from the E vs V curves and the values plotted. Approximate first derivative curves, $\Delta E/\Delta V$ of Figure 3, are drawn and smoothed to bell shape. The rate of change of potential for each 0.01‰ can then be found from the bell curves and approximate curves drawn for the second derivatives, $\Delta^2E/\Delta V^2$ of Figure 3. The first derivative curves are bell shaped rather than cusps as in Figures 1 and 2 because ΔE was determined and plotted for very small intervals of ΔV. The second derivative curves are flattened for the same reason.

The inevitable errors in the observed values of E will be magnified in the first and second derivative curves. A rational means of compensating for these errors is by curve smoothing. As the first derivative curve is drawn, more probable values for some of the points will be indicated, and corresponding corrections may be applied to the E vs V plot. As the second derivative curve is plotted,

TABLE 1 – *Observed potentials for three titrations with first and second derivatives calculated for one*

V	Titration replicates				
	C	B	A		
	E	E	E	$\Delta E/\Delta V$	$\Delta^2E/\Delta V^2$
per mille	mv	mv	mv		
17.60	...	...	16		
				30	
17.70	13	5	19		10
				40	
17.80	...	...	23		30
				70	
17.90	24	16	30		−10
				60	
18.00	...	...	36		20
				80	
18.10	40	30	44		50
				130	
18.20	...	...	57		110
				240	
18.30	76	70	81		680
				920	
18.40	172	169	173		−610
				310	
18.50	...	...	204		−170
				140	
18.60	218	218	218		−50
				90	
18.70	...	...	227		0
				90	
18.80	...	231	236		−70
				20	
18.90	...	...	238		20
				40	
19.00	247	243	242		20
				10	
19.10	...	...	248		−50
				10	
19.20	...	...	249		

corrections will be indicated for the other two curves. If the indicated corrections seem excessive, the derivative curve is modified accordingly. This process is continued until the curves are mutually consistent. The curves may not be quite symmetrical when completed, but the smoothing process should not be forced beyond reasonable corrections in the observed values of E. From the smoothed curves in Figure 3, the endpoints of titrations B and C are found to be 18.351 and 18.363‰ respectively and to occur at 123 mv.

This sort of graphical analysis is very satisfying and something of this nature, or a refined mathematical analysis, is necessary for precise physical chemical work. For routine sea-water titration, however, the equivalence point potential can be determined with sufficient accuracy for use as the titration endpoint by (1) inspection of the graph of E vs V or of the first derivative, (2) inspection of numerical values of the first derivative calculated from the E vs V data, or (3) using numerical values of the second derivative as described below.

Numerical analysis, first derivative—The increases in electrode potential ΔE for equal successive additions of silver nitrate solution ΔV are found, as in Table 1 [*Hostetter and Roberts*, 1919]. The values of $\Delta E/\Delta V$ should follow the trend described by the dashed curves of Figures 1 and 2. The endpoint may be interpolated from the ΔV interval for which $\Delta E/\Delta V$ is greatest. If the interval is too small, the $\Delta E/\Delta V$ values will usually be erratic because the electrodes come to equilibrium slowly. The maximum observed value of $\Delta E/\Delta V$ may not be at the equivalence point in this case. When ΔV is small, it will thus be necessary to select a central value of $\Delta E/\Delta V$, around which other values are distributed symmetrically (this is a mental form of graphical analysis).

Without graphing or going to rather cumbersome methods of analysis, the first derivative alone does not always give a ±0.01‰ volume determination, but examination of Table 1 and Figures 2 and 3 indicates that it is satisfactory for selection of a titration endpoint potential.

Numerical analysis, second derivative—Values of $\Delta^2E/\Delta V^2$ are determined for volume increments of 0.02 to 0.1‰, as shown in Table 1. The greatest absolute values of $\Delta^2E/\Delta V^2$ will occur when the function changes sign. The endpoint volume is then determined by

$$V_{ep} = V_1 + \Delta V \frac{(\Delta^2E/\Delta V^2)_1}{(\Delta^2E/\Delta V^2)_1 - (\Delta^2E/\Delta V^2)_2} \quad (1)$$

where V_1 is the volume at which the first large value of the second derivative $(\Delta^2E/\Delta V^2)_1$ occurs,

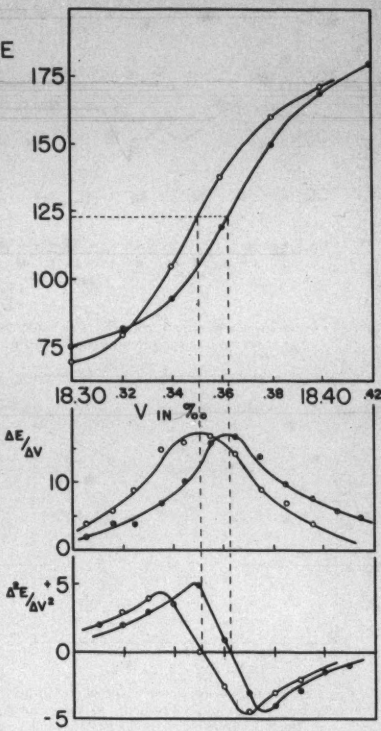

FIG. 3 – Smoothed curves (see text)

and $V_1 + \Delta V$ is the volume at which the second large value $(\Delta^2E/\Delta V^2)_2$ occurs. Using the data of Table 1, the volume at the endpoint is

$$18.30 + 0.10 \times 68/(68 + 61) = 18.353‰$$

which is in agreement with the values estimated from Figures 2 and 3.

Calculations using (1) will give precise volume and potential values for the titration endpoint, but this is not a very rapid or convenient method for routine work.

Titration to pre-determined endpoint—Once the equivalence potential has been determined, the vacuum-tube millivoltmeter may be set to this potential and subsequent titrations made following the general procedures of Knudsen but using the meter instead of a color change to indicate the endpoint. (Some instruments are read in arbitrary

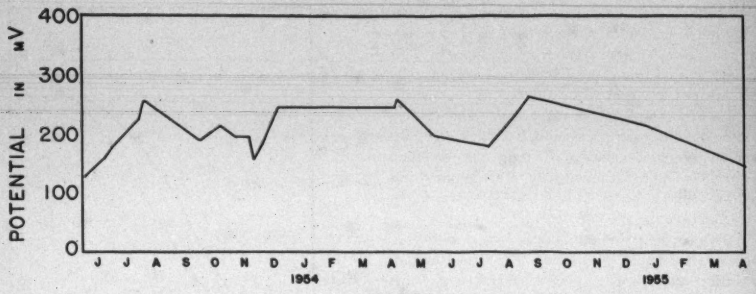

FIG. 4 – Variation of equivalence potential with time; the line connecting the successive endpoint potentials has little or no significance; several periods when no titrations were done are included in this graph

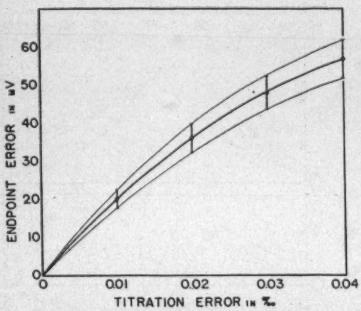

FIG. 5 – Potential change on each side of the titration endpoint; average of 18 titrations, 36 values for each point; the thin curves are the probable error limits

units rather than in millivolts. The manipulation is the same, however.) This is generally the most satisfactory method for chlorinity titrations.

Electrode stability—Ag indicating electrodes and Ag-AgCl reference electrodes are available commercially for the titration of halides with $AgNO_3$. These electrodes have not given a constant equivalence point potential in routine use with the *Harwell* [1954] or the Proctor (unpublished) titration instruments, as Figure 4 will show. While this drift in electrode potential is alarming at first glance, it will be shown that drifts of this magnitude are not significant sources of error in the Knudsen method where samples are compared with a standard of similar halide content.

If a sudden, undetected shift of equivalence point potential occurs between the titrations of the standard and of the samples, significant error could result. Such a shift of electrode potential coming between two titrations would have to be at least 20 mv, probable error (equal to 0.675 standard deviations) 2.5 mv, before an error of 0.01‰ (1/2000 for the average sea water sample) would be introduced (see Fig. 5). Any sudden shifting of this or greater magnitude would show up during the course of the titrations in one or more of the following ways: (1) poor agreement of replicate titrations, (2) significant shift in titration value of the substandard (or standard) sea water which is run after each five to ten samples, or (3) sluggish response of the indicating instrument near the endpoint of the titration. Such behavior would scarcely escape the attention of the operator, so remedial steps would be taken before the chlorinity values were reported to the cruise data analysis group.

Individual titration errors—Data from 18 titrations on seven different samples were analysed to find out what errors in endpoint potential would result in titration errors of 0.01, 0.02, 0.03, and 0.04‰ chlorinity. Errors before and after the endpoint were considered so that 36 values were averaged for each point on the heavy curve in Figure 5. The standard deviation and the probable error were computed for each point. The probable error curves are the thin lines in Figure 5. If an endpoint were missed by five mv, reference to the graph shows that the titration would be in error by only 0.0022‰ from this cause.

Errors in endpoint potential—The errors discussed in the preceding section were due to deviation of the endpoint of an individual titration from the true values. These error values are not directly applicable if the millivoltmeter is not set to the proper potential. If the meter were set 50 mv too high, each sample would be over-titrated by about

0.032‰, the value given by Figure 5. If the endpoints of duplicate titrations now differ by five mv, the two titrations will still differ by only 0.005 or 0.006‰ from this cause. (These are the extrapolated volume errors from Fig. 5 for 50 ± 5 mv.)

Systematic errors that apply equally to all titrations, such as an error in meter setting, are of little importance when the standard solution and the samples are of nearly the same concentration. From the equation that follows, it is possible to calculate the systematic errors that can be tolerated for various concentration ratios between sample and standard solutions in the Knudsen method.

Let A = chlorinity of standard solution, ‰
B = chlorinity found for sample
$B \pm 0.01$‰ = true chlorinity of sample
ΔV = maximum value of systematic error (+ or −) so that error in reported value will not exceed 0.01‰.

Then

$$\frac{A}{A + \Delta V} = \frac{B \pm 0.01\text{ ‰}}{B + \Delta V} \qquad (2)$$

After expansion and discarding of the infinitesimal 0.01‰, (2) simplifies to

$$\Delta V = \pm 0.01 \frac{A}{A - B} \qquad (3)$$

(See Appendix for more exact development.)

The positive values found for ΔV were plotted in Figure 6. The ΔE values were determined with the aid of Figures 5 and 2.

Comparison with colorimetric endpoints—The chromate and potentiometric endpoints were compared and the data from two titrations summarized for Table 2. To attain a recognizable color change, it was necessary to go about 0.05‰ (23 mv) past the potentiometric endpoint. Calculations based on (3) indicate that this will result in errors of less than 0.005‰ in the reported chlorinity values for samples between 17.5 and 21.4‰ but that errors as large as 0.01‰ will result for samples of 15.5 and 23‰ when Standard Sea Water of 19.5‰ is used for comparison.

Summary and conclusions—The day-to-day variations of electrode potential at the titration endpoint as shown in Figure 4 may be treated as a source of systematic error because the error applies equally to the titration of samples and standards. Figure 6 shows that these systematic errors must be quite large, about 0.05‰ or 65 mv, before an error of 0.01‰ is introduced in the reported chlorinity values for deep-water samples. Significant titration errors from this source are unlikely, as such a large shift in electrode potential would give sluggish meter response and erratic titration values. The operator would thus know when to check the endpoint potential.

TABLE 2 – *Comparison of colorimetric and potentiometric endpoints*

Item	Titration replicates	
	1	2
Colorimetric endpoint (chromate indicator)		
V	19.380 ‰	19.370 ‰
E	306 mv	308 mv
Potentiometric endpoint (calculated from second derivatives)		
V	19.329 ‰	19.325 ‰
E	183 mv	185 mv
Overshoot by colorimetric method		
ΔV	0.05 ‰	0.05 ‰
ΔE	23 mv	23 mv

A satisfactory endpoint potential may be determined by inspection of the numerical values of potential change (first derivative) as equal portions (0.02 to 0.1‰) of silver nitrate are added near the equivalence point. The meter is set and samples are titrated to this endpoint. Satisfactory salinity values for routine deep-sea samples should be obtained if the equivalence point potential is determined to ten mv and individual titrations are within five mv of this endpoint. Titrations are made to the exact endpoint, but the potential may drift slightly as the electrodes come to equilibrium.

Examination of the potentiometric method has shown that drift of the indicating electrode, as shown in Figure 4, and small differences in the endpoint potential of individual titrations are not significant sources of error in the titration of deep-sea samples. Two years of experience with the method in this laboratory has failed to show any reason for returning to the colorimetric endpoint.

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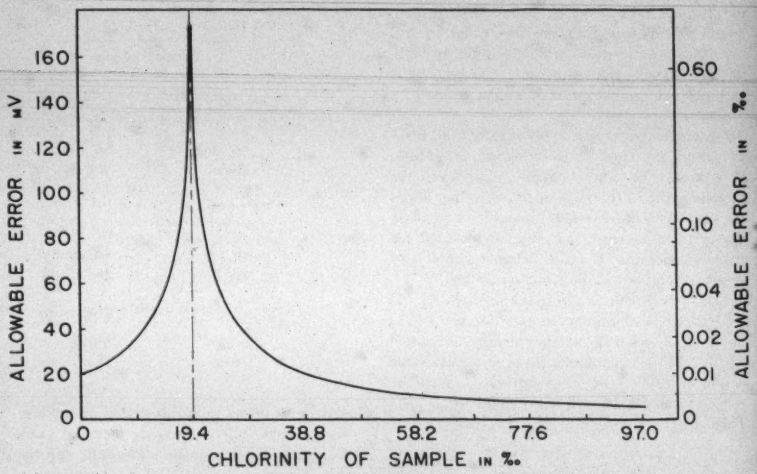

FIG. 6 – Maximum allowable systematic (constant) endpoint errors for samples of various chlorinities when compared with a standard sea water of 19.4‰; the resulting error in reported chlorinity value from this cause will be 0.01‰

APPENDIX

Allowable systematic errors—The amount of $AgNO_3$ needed to titrate a sea-water sample can be expressed in terms of ‰ Cl equivalents, that is, in terms of the amount required to titrate the usual sample of sea water to the exact, stoichiometric endpoint. Under ideal conditions, the $AgNO_3$ solution would contain one ‰ Cl equivalent in one double ml, so that the numerical titration value exactly equals the chlorinity.

Let E be the true equivalence point potential, and assume that the meter is set to $E + \Delta E$ and that ΔV is the resulting error in titration volume. Let the strength of the $AgNO_3$ solution be adjusted so that the volume V_A used in titrating a sample of standard sea water equals the chlorinity A of the standard. The true endpoint will have been at $V_A - \Delta V$ or $A - \Delta V$. The $AgNO_3$ solution will then be stronger than the stoichiometric value, its strength being $A/(A - \Delta V)$‰, and the amount of $AgNO_3$ used for the titration will be $A^2/(A - \Delta V)$‰.

In titrating a sample of chlorinity B, the volume of $AgNO_3$ solution required to reach the endpoint will be $B(A - \Delta V)/A$‰, the stoichiometric quantity, plus ΔV, the error volume. The amount of $AgNO_3$ used will be the volume times the strength of the solution

$$\left(B\frac{A-\Delta V}{A}+\Delta V\right)\frac{A}{A-\Delta V} = B + \frac{A\Delta V}{A-\Delta V} = AgNO_3 \text{ used} \quad (4)$$

For a maximum error of 0.01‰ in B, the allowable endpoint error (ΔV) can be determined for various ratios of sample B to standard A chlorinity by the following method where

Cl = chlorinity of a sample or standard

$AgNO_3$ = equivalent amount of $AgNO_3$

$$\frac{Cl}{AgNO_3} = \frac{A}{A^2/(A-\Delta V)} = \frac{B \pm 0.01\text{ ‰}}{(B + A\Delta V)/(A-\Delta V)} \quad (5)$$

$$\frac{A-\Delta V}{A} = \frac{(B \pm 0.01\text{ ‰})(A-\Delta V)}{AB - B\Delta V + A\Delta V} \quad (6)$$

$$AB - B\Delta V + A\Delta V = AB \pm 0.01A\text{ ‰} \quad (7)$$

$$\Delta V(A - B) = \pm 0.01A\text{ ‰} \quad (8)$$

$$\Delta V = \pm 0.01\ A/(A - B)\text{‰} \quad (9)$$

Eq. (9) is the same as (3), previously found and plotted in Figure 5.

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The Theory of the Transient State Concerning Upwelling and Coastal Current

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Abstract—Upwelling in the Gulf of Mexico and along the coast of California has been treated theoretically by Hidaka for steady-state conditions. An extension of this work is presented which considers the transient state in which upwelling and coastal currents gradually develop in an ocean initially at rest when the wind suddenly begins to blow over the sea surface. Expressions for the component velocity in the x and y directions, for the vertical component, and for the vorticity in the direction of the z axis are derived. A numerical example is included using the expression derived for the x component of the current.

The problem treated in this paper is the one concerning upwelling and coastal currents caused by the local wind action near the coast. The effect of the latitude variation of the Coriolis parameter will not be taken into account, because the region of the ocean under consideration is a small scale.

The explanation of the upwelling off California given by *Sverdrup* [1938] is worth attention. According to *Sverdrup* and *Fleming* [1941], it is known from analysis of the water masses that water taking part in the process of upwelling off the coast of Southern California originates mostly in the layer from 200 to 300 m below the surface. It has been noticed that the upwelling occurs most favorably when in the northern (southern) hemisphere, a wind blows in such a manner that the coast is on the left-hand (right-hand) side of an observer who looks in the direction of the wind. Thus, the upwelling off the coast of California is most marked in early summer when northwesterly wind prevails for several weeks parallel to the coast.

In the Gulf of Mexico, prevailing easterlies occur almost all year around. This means that we can usually expect upwelling along the northern coast of Cuba and the northern Yucatan coast. And it is known that there are upwelling and colder water off these coasts, and many vessels fish in the waters off Yucatan.

Recently, on the basis of the circumstances mentioned above, *Hidaka* [1954] made a theoretical treatment concerning the upwelling by taking the effect of the Earth's rotation and the frictional forces due to both vertical and horizontal mixing into account. However, his treatment was only for a steady state. In this paper, the author will discuss the manner in which the upwelling and coastal currents gradually develop in an ocean initially at rest, when the wind suddenly begins to blow over the sea surface. Accordingly, in this investigation the problem of the transient state of upwelling and coastal currents will be attacked.

Theory of the transient state of upwelling and coastal currents caused by a wind—Consider a straight coast coincident with the y axis, with the x axis perpendicular to it in the offshore direction. Take the z axis vertically upward from a sea surface. Assume a wind of a constant force and direction which suddenly begins to blow, in a belt of limited width ℓ, where the wind is directed in the angle of counterclockwise positive direction from the x axis toward the y axis (Fig. 1).

If a constant wind begins to blow, a transient state will occur in which the motion of water is dependent on time. It is assumed that the wind stress cannot vary in the y direction, but is a function of x. Therefore, the vertical and horizontal components of currents can be determined as functions of x, z, and t.

The surface of the sea will usually have a slope in the x direction. However, when the sea is sufficiently deep and no density stratification exists then the surface slope will disappear. In such a case, the hydrodynamic equation of motion is

$$\frac{\partial W}{\partial t} = \nu_x \frac{\partial^2 W}{\partial x^2} + \nu_z \frac{\partial^2 W}{\partial z^2} - i2\tilde{\omega} W \qquad (1)$$

where $W = u + iv$, u and v being the components of horizontal velocity in the x and y directions respectively; $\tilde{\omega} = \omega \sin \phi$, ω being the angular rotation of the Earth and ϕ the latitude; and ν_x and ν_z are the kinematic eddy viscosity coefficients for horizontal and vertical mixing. In the following development ν_x and ν_z are assumed constant. Since the density is regarded as constant and the velocities are considered independent of

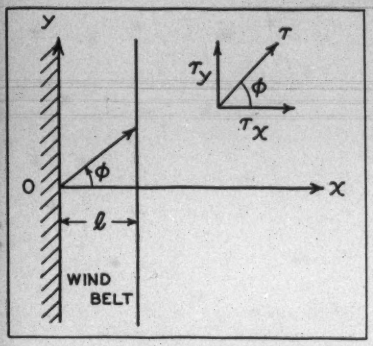

FIG. 1 – Elements of the problem

y, it follows that the vertical velocity w (positive upward) is governed by

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

because of continuity of mass.

The assumed initial condition is

$$W(x, z, 0) = 0 \tag{3}$$

and the boundary conditions to be satisfied are

$$\rho\nu_z \left.\frac{\partial W}{\partial z}\right|_{z=0} = \begin{cases} \tau, & 0 < x < \ell \\ 0, & x > \ell \end{cases} \tag{4}$$

where $\tau = \tau_x + i\tau_y$ is the wind stress vector whose components τ_x and τ_y are assumed constant in the wind belt zone of width ℓ; and

$$W(x, -\infty, t) = 0 \tag{5}$$

$$\left.\frac{\partial W}{\partial z}\right|_{z=-\infty} = 0 \tag{6}$$

$$W(0, z, t) = 0 \tag{7}$$

$$W(\infty, z, t) = 0 \tag{8}$$

$$\left.\frac{\partial W}{\partial x}\right|_{x=\infty} = 0 \tag{9}$$

To solve (1), we make use of the method of Stokes. Then, with the aid of the boundary conditions (7), (8) (9), we have

$$\frac{\partial V}{\partial t'} = \frac{\partial^2 V}{\partial z^2} - \left(\frac{\nu_x}{\nu_z}\alpha^2 + i\frac{2\tilde{\omega}}{\nu_z}\right) V \tag{10}$$

where W is the Fourier sine transform of V such that

$$W = \frac{2}{\pi}\int_0^\infty V \sin \alpha x \, d\alpha \tag{11}$$

and $t' = \nu_z t$.

The wind stress vector τ can be represented by

$$\tau = \frac{2}{\pi}\int_0^\infty \bar{\tau} \sin \alpha x \, d\alpha \tag{12}$$

where

$$\bar{\tau} = \int_0^\infty \tau \sin \alpha\lambda \, d\lambda = \int_0^\ell \tau \sin \alpha\lambda \, d\lambda = \frac{\tau(1 - \cos \alpha\ell)}{\alpha} \tag{13}$$

Therefore the initial and the remaining boundary conditions (4), (5), and (6). are

$$V|_{t'=0} = 0 \tag{14}$$

$$\rho\nu_z \left.\frac{\partial V}{\partial z}\right|_{z=0} = \frac{\tau(1 - \cos \alpha\ell)}{\alpha} \tag{15}$$

$$V|_{z=-\infty} = 0 \tag{16}$$

and

$$\left.\frac{\partial V}{\partial z}\right|_{z=-\infty} = 0 \tag{17}$$

In a similar manner, by virtue of the boundary conditions (15), (16), (17), we can transform (10) into

$$\frac{\partial U}{\partial t'} = \frac{\tau(1 - \cos \alpha\ell)}{\rho\nu_z\alpha} - \gamma^2 U - \left(\frac{\nu_x}{\nu_z}\alpha^2 + \frac{i2\tilde{\omega}}{\nu_z}\right) U \tag{18}$$

where V is the Fourier cosine transform of U such that

$$V = \frac{2}{\pi}\int_0^\infty U \cos \gamma z \, d\gamma \tag{19}$$

The solution of this equation is

$$U = \frac{\tau(1 - \cos \alpha\ell)}{\rho\nu_z\alpha} \cdot \frac{1 - \exp\left\{-\left(\frac{\nu_x}{\nu_z}\alpha^2 + \gamma^2 + \frac{i2\tilde{\omega}}{\nu_z}\right)t'\right\}}{\frac{\nu_x}{\nu_z}\alpha^2 + \gamma^2 + \frac{i2\tilde{\omega}}{\nu_z}} \tag{20}$$

under the initial condition $U|_{t=0} = 0$.

Therefore, substituting from (20) into (19) and (11)

$$W = \frac{4}{\pi^2}\int_0^\infty\int_0^\infty \frac{\tau(1-\cos\alpha\ell)}{\rho\nu_z\alpha} \cdot \frac{1-\exp\left\{-\left(\frac{\nu_z}{\nu_s}\alpha^2+\gamma^2+\frac{i2\tilde{\omega}}{\nu_s}\right)t'\right\}}{\frac{\nu_z}{\nu_s}\alpha^2+\gamma^2+\frac{i2\tilde{\omega}}{\nu_s}} \cdot\sin\alpha x\cos\gamma z\,d\alpha\,d\gamma \quad (21)$$

This expression can be considered as consisting of two parts, of which one, not including the variable of time, represents the steady state, and the other, with an exponential term of time, represents the decaying state of the current should the wind suddenly cease.

Eq (21) can be rewritten as

$$W = \frac{1}{\sqrt{\pi}}\frac{\tau}{\rho\nu_s}\int_0^{t'}\frac{1}{\sqrt{t'}}\exp\left[-\left(\frac{z^2}{4t'}+\frac{i2\tilde{\omega}}{\nu_s}t'\right)\right] \cdot\left[\Phi\left(\frac{x}{2\sqrt{\frac{\nu_z}{\nu_s}t'}}\right) -\frac{1}{2}\left\{\Phi\left(\frac{x+\ell}{2\sqrt{\frac{\nu_z}{\nu_s}t'}}\right)+\Phi\left(\frac{x-\ell}{2\sqrt{\frac{\nu_z}{\nu_s}t'}}\right)\right\}\right]dt' \quad (22)$$

where

$$\Phi(a) = \frac{2}{\sqrt{\pi}}\int_0^a e^{-x^2}\,dx \quad (23)$$

The development is outlined in the Appendix. The exponential term in (22) is the effect due to vertical mixing, and the bracketed quantity is due to horizontal mixing.

Here let us define D_s and D_z by

$$D_s = \frac{\pi}{\sqrt{\frac{\tilde{\omega}}{\nu_s}}}, \qquad D_z = \frac{\pi}{\sqrt{\frac{\tilde{\omega}}{\nu_z}}} \quad (24)$$

and introduce the following dimensionless variables

$$\xi = \frac{\pi}{2}\frac{x}{D_s}, \qquad \eta = \frac{\pi}{2}\frac{z}{D_s}, \qquad L = \frac{\pi}{2}\frac{\ell}{D_s}, \qquad T = \frac{\tilde{\omega}}{\nu_s}t' \quad (25)$$

D_s is the depth of frictional influence (Reibungstiefe) defined by *Ekman* [1905], and D_z, which may be called the distance of frictional influence (or frictional distance), is a measure of the horizontal turbulence.

With these variables, we can derive the velocity components u and v from (22)

$$u = \frac{1}{\pi^{3/2}}\frac{D_z}{\rho\nu_s}\int_0^T\left|(\tau_x\cos 2T+\tau_y\sin 2T)\frac{e^{-\eta^2/T}}{\sqrt{T}} \cdot\left[\Phi\left(\frac{\xi}{\sqrt{T}}\right)-\frac{1}{2}\left\{\Phi\left(\frac{\xi+L}{\sqrt{T}}\right) +\Phi\left(\frac{\xi-L}{\sqrt{T}}\right)\right\}\right]dT\right. \quad (26)$$

$$v = \frac{1}{\pi^{3/2}}\frac{D_z}{\rho\nu_s}\int_0^T(\tau_y\cos 2T-\tau_x\sin 2T)\frac{e^{-\eta^2/T}}{\sqrt{T}} \cdot\left[\Phi\left(\frac{\xi}{\sqrt{T}}\right)-\frac{1}{2}\left\{\Phi\left(\frac{\xi+L}{\sqrt{T}}\right) +\Phi\left(\frac{\xi-L}{\sqrt{T}}\right)\right\}\right]dT \quad (27)$$

while from the equation of continuity (3) we obtain

$$w = \frac{2\tau}{\pi^2}\frac{D_s^2}{D_z\rho\nu_s} \cdot\int_0^\eta\int_0^T(\tau_x\cos 2T-\tau_y\sin 2T)\frac{e^{-\eta^2/T}}{T} \left[e^{-\xi^2/T}-\tfrac{1}{2}\left\{e^{-(\xi+L)^2/T}+e^{-(\xi-L)^2/T}\right\}\right]dT\,d\eta \quad (28)$$

The above results hold only when the wind stress is constant with time. However, when the wind stress varies with time, Duhamel's theorem can be used to evaluate W

$$W(x,z,t) = \int_0^t \tau(t-\lambda)\frac{\partial W_0}{\partial\lambda}(x,z,\lambda)\,d\lambda \quad (29)$$

where W_0 is the solution at $\tau = 1$.

Numerical example—To estimate the patterns of horizontal and vertical current we must first select numerical values for the coefficients of horizontal and vertical mixing. Using the conventional value of 1000 cgs units for the coefficient of vertical mixing, we obtain a depth of frictional influence D_s of 195 m at 21° N and 162 m at 30° N. For ν_z , ν_s/ν_z is taken as approximately 10^8, which means that D_z is about 1000 times as large as D_s , or 195 km and 162 km respectively.

The stress τ is taken as 1 dyne/sq. cm, corresponding to a wind speed between 5 and 6 m/sec.

The numerical calculations can be evaluated as follows

$$\frac{u}{\frac{\tau D_s}{2\pi\rho\nu_s}} = \sum_{n=1}^{n=N}(\tau_x\cos 2n\Delta T+\tau_y\sin 2n\Delta T)\frac{\frac{2}{\sqrt{\pi}}e^{-\eta^2/n\Delta T}}{\sqrt{n\Delta T}} \cdot\left[\Phi\left(\frac{\xi}{\sqrt{n\Delta T}}\right) -\frac{1}{2}\left\{\Phi\left(\frac{\xi+L}{\sqrt{n\Delta T}}\right)+\Phi\left(\frac{\xi-L}{\sqrt{n\Delta T}}\right)\right\}\right]\Delta T$$

with similar formulas for the components v and w

$$\frac{v}{\left(\frac{1}{2\pi}\frac{D_z}{\rho\nu_z}\right)} = \sum_{n=1}^{n=N} (\tau_y \cos 2n\Delta T - \tau_x \sin 2n\Delta T)$$

$$\times \frac{\frac{2}{\sqrt{\pi}} e^{-(\eta/\sqrt{n\Delta T})^2}}{\sqrt{\quad}} \times \left[\Phi\left(\frac{\xi}{\sqrt{n\Delta T}}\right) - \frac{1}{2}\left\{\Phi\left(\frac{\xi+L}{\sqrt{n\Delta T}}\right) + \Phi\left(\frac{\xi-L}{\sqrt{n\Delta T}}\right)\right\}\right] \Delta T$$

$$\frac{w}{\left(\frac{1}{2\pi}\frac{D_z^2}{D_x \rho \nu_z}\right)} = \sum_{m=1}^{m=M} \sum_{n=1}^{n=N} (\tau_x \cos 2n\Delta T - \tau_y \sin 2n\Delta T)$$

$$\times \frac{\frac{2}{\sqrt{\pi}} e^{-(m\Delta\eta/\sqrt{n\Delta T})^2}}{n\Delta T} \times \left\{\frac{2}{\sqrt{\pi}} e^{-(m\Delta\xi/\sqrt{n\Delta T})^2} - \frac{1}{2}\left(e^{-(m\Delta\xi+L/\sqrt{n\Delta T})^2} + e^{-(m\Delta\xi-L/\sqrt{n\Delta T})^2}\right)\right\}$$

$$\times \Delta T \Delta \xi$$

In our treatment, the angle (of the wind) of the conventional counter-clockwise positive direction from the x axis toward the y axis, ϕ, is taken as 45° and the lateral distance from the coastline to the end of the wind-belt is divided into eight parts. In this discussion we will consider the circumstances of the pattern of horizontal current in the first four parts (x/Dx = 0.1396, 0.2793, 0.5585, 0.8378, $\cdots$).

The patterns of the currents changing with time show spiral curves respectively. In the beginning intervals of the time, the angles between the wind and surface current are small and almost of the same magnitude respectively. But with the progression of time, the angles of those regions which depart from the shore are less declined to the right. The mean magnitude of current in these regions also becomes stronger in comparison with the shore current.

In the final steady-state condition the angles for the values of x/Dx mentioned above are

x/Dx	0.1396	0.2793	0.5585	0.8378
angle	44°	50°	59°	63°

In the parts which depart from x/Dx = 0.8378, the angle will gradually decrease again.

It is supposed that the variation of these angles is caused by the effect of horizontal mixing.

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Appendix

Putting

$$I = \int_0^\infty \frac{1 - \exp\left\{-\left(\frac{\nu_x}{\nu_z}\alpha^2 + \gamma^2 + \frac{i2\tilde{\omega}}{\nu_z}\right)t'\right\}}{\frac{\nu_x}{\nu_z}\alpha^2 + \gamma^2 + \frac{i2\tilde{\omega}}{\nu_z}} \cdot \cos \gamma z \, d\gamma$$

we have

$$\frac{dI}{dt'} = \exp\left\{-\left(\frac{\nu_x}{\nu_z}\alpha^2 + \frac{i2\tilde{\omega}}{\nu_z}\right)t'\right\} \cdot \int_0^\infty \exp(-t'\gamma^2) \cos \gamma z \, d\gamma$$

$$= \frac{\sqrt{\pi}}{2}\frac{1}{\sqrt{t'}} \exp\left[-\left\{\left(\frac{\nu_x}{\nu_z}\alpha^2 + \frac{i2\tilde{\omega}}{\nu_z}\right)t' + \frac{z^2}{4t'}\right\}\right]$$

therefore

$$I = \frac{\sqrt{\pi}}{2}\int_0^{t'} \frac{1}{\sqrt{t'}} \exp\left[-\left\{\left(\frac{\nu_x}{\nu_z}\alpha^2 + \frac{i2\tilde{\omega}}{\nu_z}\right)t' + \frac{z^2}{4t'}\right\}\right] dt'$$

Substituting in (21), we have

$$W = \frac{2\tau}{\pi^{3/2}\rho\nu_z}\int_0^{t'} \frac{1}{\sqrt{t'}} \exp\left[-\left(\frac{z^2}{4t'} + \frac{i2\tilde{\omega}}{\nu_z}t'\right)\right] \cdot \left[\int_0^\infty \frac{(1 - \cos \alpha\ell)}{\alpha} e^{-(\nu_x/\nu_z)\alpha^2 t'} \sin \alpha x \, d\alpha\right] dt'$$

The quantity under the integral with α can be written as

$$\int_0^\infty \frac{e^{-(\nu_x/\nu_z)\alpha^2 t'}}{\alpha} \cdot [\sin \alpha x - \tfrac{1}{2}\{\sin(x+\ell)\alpha + \sin(x-\ell)\alpha\}] \, d\alpha$$

$$= \frac{\pi}{2}\left[\Phi\left(\frac{x}{2\sqrt{\frac{\nu_x}{\nu_z}t'}}\right) - \frac{1}{2}\left\{\Phi\left(\frac{x+\ell}{2\sqrt{\frac{\nu_x}{\nu_z}t'}}\right) + \Phi\left(\frac{x-\ell}{2\sqrt{\frac{\nu_x}{\nu_z}t'}}\right)\right\}\right]$$

from which we obtain (22).

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Estimating Evaporation

H. L. PENMAN

Abstract—Evaporation is a physical process that must satisfy two basic requirements. There must be an energy supply to provide heat of vaporization; and there must be some transport mechanism for removing the vapor. Combining these concepts it is possible to derive an expression for evaporation rate that depends only on measureable weather elements. By making some simplifying approximations, the weather data needed reduce to (a) duration of bright sunshine, (b) air temperature, (c) air humidity, and (d) wind speed. The quantity obtained is E_O, the evaporation rate for a hypothetical open water surface exposed to the measured weather. Formally, and empirically, it is possible to convert E_O into E_T, the potential transpiration rate from a short green crop cover, completely shading the ground and never short of water. This computation has formed the basis of successful experiments in irrigation control; and, with reasonable empirical modification to allow for conditions when water supply becomes a limiting factor, has been applied with some success in studies of the water balance of catchment areas. Applied to two classical American watershed studies it suggests that some of the Coweeta results may need reconsideration.

Water balance and energy balance—Of the two important conservation principles, hydrologists make full use of one as something self-evident: The rain falling on a watershed either stays in the watershed or leaves it. If natural periods can be chosen at the beginning and end of which the water content of the catchment is the same then the conservation principle reduces to: rainfall is equal to losses, and the losses can be separated into loss as liquid and loss as vapor. If the catchment is impervious, and watertight except for surface streams, then the conservation equation for natural periods reduces to the familiar form: rainfall = runoff + evaporation.

Many of the analyses of catchment behavior are based on this equation: its validity is conditional upon the absence of leaks. In general, the hydrogeological problem is so difficult that the absence of leaks has to be an article of faith, and it is rarely possible to be able to make a statement as confident as: "There is no indication of any quantity of seepage escaping measurement."

Direct check being impossible, it is worth while seeking an indirect check and this can be obtained if an independent estimate of evaporation can be made. There is more than one way of doing this, but the use of the second great conservation principle offers a way of getting a physical estimate, and also provides a by-product of almost equal importance in hydrology. Put in its self-evident form, the second conservation principle is: All the energy falling on a catchment either stays in the catchment or leaves it. For a natural period of the order of a year long the energy retained in the catchment is a very small part of the whole, and even for shorter periods of the order of a month is usually negligible. The conservation equation is thus: energy income is equal to energy losses. The energy income is from solar radiation; the main losses are (1) reflection of solar radiation (a short-wave energy loss), (2) net back radiation to the atmosphere (a long-wave energy loss), and (3) evaporation (a latent-heat loss). For short-period balances a fourth must be added, namely heat transfer to (or from) the air (a sensible heat transfer). In symbols

$$R_I = rR_I + R_B + E + K$$

where R_I is short-wave income, r is the reflection coefficient, R_B is the net long-wave radiation outward, E is the evaporation, and K is the sensible heat transfer to the atmosphere, all expressed in the same unit (1 cm evaporation = 590 cal/cm²). Rearranging

$$E + K = R_I(1 - r) - R_B = H$$

Restricting discussion to the case of a fully vegetated catchment, important conclusions can be drawn from the right-hand side of this equation. The income R_I is independent of the surface it reaches, and is a purely meteorological quantity. The reflection coefficient r is a surface property but has a value not far from 0.20 for most green vegetation. The back radiation R_B is almost independent of surface properties, and appears to be dependent on mean air temperature, degree of cloudiness, and atmospheric humidity; that is, it too is a meteorological quantity. Hence, apart from differences in color, the quantity H (known as the heat budget) is primarily dependent on the

weather, and for two areas exposed to the same weather should be substantially the same for both, that is, the value of $E + K$ for the two areas should be substantially the same. If now (again merely to limit discussion) it is postulated that water supply in the areas is sufficient to maintain full transpiration then the ratio of K/E is usually small and approximately constant, at least during summer when evaporation is greatest. From this, as a very good first approximation, it is possible to state that the evaporation from two vegetated areas exposed to the same weather will be the same for both, the amounts being dictated by the weather, with plant types and soil types being only minor factors.

Energy-balance estimate of evaporation: open water—This is a very useful qualitative statement. It becomes more useful when it is made quantitative, a process that needs knowledge of (a) the incoming radiation, (b) the dependence of back radiation on other weather parameters, and (c) the physical processes that determine how the heat budget is shared between E (latent-heat transfer) and K (sensible-heat transfer).

The meteorology of these energy exchanges is still far from complete, but is sufficiently advanced for adequate estimates to be made now. The estimates will be improved as fundamental knowledge becomes more certain. To get a quantitative estimate of evaporation a somewhat indirect approach is used, and though it has been shown to be unnecessary [*Penman*, 1953] it is much more convenient to make this approach through a hypothetical open water surface. As the argument and the reasons for this route have already been presented in full several times [*Penman*, 1948, 1949a, 1953] only a brief summary should be needed here to explain the working equations derived.

First the heat budget is established. Using the obvious suffix for open water, it is

$$H_O = R_I(1 - r_O) - R_B$$

The incoming energy can be estimated adequately enough from the known maximum possible for the site in the absence of an atmosphere (R_A, dependent on the solar constant, latitude, and time of year, and obtainable from standard tables), and from the ratio of actual to possible hours of bright sunshine. The reflection coefficient for open water is taken as $r = 0.05$. Back radiation has been empirically correlated with weather parameters including cloudiness. It is assumed that average cloudiness can be estimated from average duration of sunshine. Then

$$H_O = 0.95\,R_A\,(0.18 + 0.55\,n/N) - \sigma T_a^4\,(0.56 - 0.09\,\sqrt{e_d})(0.10 + 0.90\,n/N),$$

where

R_A = Ångot value of maximum possible radiation
n/N = duration of bright sunshine/possible duration
σT_a^4 = black body radiation at mean air temperature T_a
e_d = mean air humidity (mm Hg)

Another equation is needed, to separate E and K. The simple empirical form of the aerodynamic equation for evaporation is adequate. It is

$$E_O = f(u)(e_s - e_d)$$

where $f(u)$ is a function of wind velocity, e_s is the saturation vapor pressure at the surface of the water, and e_d is the vapor pressure in the air above. Assuming equivalence in the turbulent transport constants a similar equation can be written down for sensible heat transfer

$$K_O = \gamma f(u)(T_s - T_a)$$

where γ is a constant (actually the psychrometer constant) needed to keep units consistent, and T_s is the surface temperature of the water.

Introducing a new, derived, parameter, $E_a = f(u)(e_a - e_d)$, where e_a is the saturation vapor pressure at mean air temperature, and the slope Δ of the saturation vapor pressure curve at T_a, simple algebra leads to

$$E_O = (\Delta H_O + \gamma E_a)/(\Delta + \gamma)$$

Everything needed in this equation can be obtained from standard weather observations and appropriate tables of constants.

Recently, as a result of the Lake Hefner studies, the form of $f(u)$ has been modified. Originally it was $f(u) = 0.35(1 + u_2/100)$ where u_2 is the wind speed in miles per day at a height of two meters. First used in a study of evaporation over parts of Europe [*Penman*, in press] the present form is

$$f(u) = 0.35\,(0.5 + u_2/100)$$

Potential transpiration—The potential transpiration, E_T, is simply obtained from this value of E_O. As a convenience it is done empirically from the equation

$$E_T = fE_O$$

the factor f having the values 0.6 for November to February, 0.8 for May to August, and 0.7 for the

other four months. These values are for southeast England, and depend primarily on length of day. There is some theoretical justification for them [*Penman*, 1953] which indicates that towards the equator they will converge on a value near 0.7 in humid regions, and on a somewhat smaller value in semi-arid regions.

The value of E_T so obtained is for a fresh green crop, of about the same color as grass, completely shading the ground, of fairly uniform height, and never short of water. Where water is a limiting factor, as it often is even in England, the actual evaporation rate will be less than the potential rate, but it is possible to make some allowance for this provided water shortage does not become too extreme [*Penman*, 1949b].

Using this weather-based method of estimating evaporation from vegetated surfaces, corrected where needed for limited available water, a wide range of applications has given encouraging agreement with such practical checks as were possible. These have included studies of the performance of field drains, water balance studies on catchment areas, evaporation maps of the British Isles and parts of Europe, control of irrigation operations, and the estimation of the frequency of irrigation need in southeast England. (A survey of part of this work appears in *Penman* [1951]). In addition there have been occasional single tests on data from other parts of the world and these too have been generally satisfactory.

Application to American watersheds—To show how the method works in an American context two examples are now given in which the main emphasis is on its diagnostic value in the type of problem set out in the opening paragraph of this paper.

At Wagon Wheel Gap [*Bates* and *Henry*, 1928] and at Coweeta [*Hoover*, 1944] pairs of neighboring catchments were compared before and after accidental or deliberate changes were made in one of the pair. If there is no appreciable leakage from either of the catchments in the pair, then (1) the difference between mean annual rainfall and mean annual runoff should be the same for both before the changes, and (2) this equal difference should be equal to (or less than, if rainfall is inadequate) the potential transpiration as calculated from weather data.

For Wagon Wheel Gap the (rounded-off) values of rainfall and runoff were equal for both areas before cutting, at 21 and 6 inches respectively. Condition (1) is satisfied, giving $R - r = 15$ inches per annum. A very rough calculation based on the weather data supplied by Bates and Henry gives an estimated value of E_T W 16 inches. Considering the unavoidable crudeness of the estimate, this is surprisingly well in agreement with $R \simeq r$, suggesting that condition (2) is satisfied. On this evidence there is no reason to question the watertightness of either of the test areas.

For Coweeta the conclusion is less satisfactory, and so needs a little more detail to show how it is reached. For the four complete years before the change in Watershed 17 the mean annual values were

$$R = 69.6 \text{ inches}$$
$$r_{17} = 27.9 \text{ inches} \quad R - r_{17} = 41.7 \text{ inches}$$
$$r_{18} = 34.1 \text{ inches} \quad R - r_{18} = 35.5 \text{ inches}$$

Condition (1) is not satisfied; this discrepancy of 6.2 inches per annum is too great to be accepted on the basis of energy balance.

To estimate potential transpiration mean weather data for Asheville, N. C., for the five years 1928–32 inclusive were used, these being the latest immediately available. Sunshine fractions have been derived from published cloudiness on the basis $n/N = 1 - m/10$ where $m/10$ is the average cloudiness. This difference in period is unlikely to be important, as potential transpiration is a remarkably conservative climatic element from year to year, and in general the years 1928–32 were above average in air temperature. The calculated mean annual value of E_0 (the sum of twelve monthly means) was 39.7 inches. Using the English values of f, which almost certainly will overestimate E_T in North Carolina, the computed values are in Table 1. Corrections for the heat content of the soil would decrease the maximum slightly, and make it later in the year. At the moment only the annual total is needed.

Condition (2) is not satisfied for either area. For Watershed 17 the rainfall minus measured runoff is 42 inches; for Watershed 18 it is 36 inches; the meteorological estimate of vapor loss is 30 inches for both areas. The inference that the water-balance figures are wrong (by 12 inches per annum in Watershed 17 and by 6 inches per annum in Watershed 18) is conditional on the evaporation estimate being right. No absolute check is possible, but there are two pieces of supporting evidence.

TABLE 1 – *Estimated potential transpiration at Asheville in inches*

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year
0.7	1.1	2.0	2.7	4.0	4.8	4.8	4.0	2.4	1.7	0.8	0.6	29.6

At the intermediate stage, the open water evaporation was calculated as 40 inches per annum. Considering the elevation of Asheville this is in extremely good agreement with the value indicated by *Horton's* [1943] evaporation map of the United States. At the final stage, the long term mean annual loss from the large catchment of the Neuse River is known to be 31.5 inches [*Langbein*, 1949], agreeing as well as can be expected with the Asheville estimate of 29.7 inches.

With this double circumstantial check it seems reasonable to suggest that the data and conclusions of *Hoover* [1944] might be re-examined. (As this is one of the key papers in the literature of hydrology, I have already passed this suggestion on to the Director of the Coweeta Forest Experiment Station, and he has paid me the compliment of taking it seriously.) This is not the place for such a re-examination; it is best done by those on the spot who know the area and its geology.

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Discussion

Harry F. Blaney (Agricultural Research Service, U. S. Department of Agriculture, Los Angeles, Calif., received June 21, 1955)—This paper should give American hydrologists and hydraulic engineers a clearer conception of the two methods Penman and Schofield have developed at the Rothamsted Experimental Station in England for determining evapotranspiration from evaporation and meteorological data. In the summer of 1954, I had the pleasure of visiting this remarkable station. To those who are not familiar with the previous writings by Penman, it should be pointed out that terms 'evaporation' and 'potential transpiration' used by him usually have the same meaning as the term 'potential evapotranspiration.'

The conservation equation rainfall = runoff + evaporation mentioned by Penman may be expressed also as evapotranspiration = rainfall − runoff when referring to a mountain watershed. However, when referring to an irrigated valley (or basin), it may be written: evapotranspiration = inflow − outflow ± change in groundwater storage; where inflow = stream-flow (river and irrigation canal) into the valley + rainfall on valley floor; and outflow = stream flow (river or drainage canal) out of the valley. This equation was used by *Israelsen* and *Blaney* [1938] in estimating evapotranspiration (consumptive use) for large valleys in New Mexico and Colorado in the Joint Rio Grande Investigation.

Studies by *Blaney* [1933] and others confirm the findings of Penman that evaporation from an open water surface may be used to estimate evapotranspiration by vegetative cover. The results of these studies indicate that the quantity of water used by tules is 95 pct of the evaporation from a U. S. Weather Bureau pan under coastal and desert weather while the evapotranspiration of irrigated alfalfa is 66 pct of pan evaporation or about the same as evaporation from a lake surface. Measurements of evapotranspiration in arid and semi-arid areas of western United States indicate that plant and soil types are major factors in evapotranspiration rather than 'minor factors' as found by Penman under weather conditions in England. For example, measurements made in San Fernando Valley, California, by *Blaney* and *Stockwell* [1940] show annual transpiration use of alfalfa to be 47 inches and by orange trees, 24 inches. Studies by *Blaney* and *Harris* [1951] in Arizona indicate that transpiration use varies with kind of vegetation.

The application of Penman's method of esti-

TABLE 2 – *Estimated normal monthly evapotranspiration based on 46-year mean meteorological records at Ashville, North Carolina*

Month	Mean monthly			Daytime hours	Factor	Coef.	Potential evapotranspiration	
	Rainfall	Temp.	Wind move.				Blaney[a]	Penman[b]
		t		p	f	k	u	
	inch	°F	mi/hr	pct			inch	inch
Jan.	2.84	38.8	9.6	7.03	2.73	0.4	1.1	0.7
Feb.	2.77	39.5	10.1	6.87	2.71	0.4	1.1	1.1
Mar.	3.60	47.0	10.2	8.35	3.92	0.5	2.0	2.0
Apr.	2.94	55.0	9.5	8.84	4.86	0.5	2.4	2.7
May	3.17	63.0	7.8	9.78	6.16	0.6	3.7	4.0
June	3.81	70.3	6.6	9.80	6.89	0.7	4.8	4.8
July	4.54	73.0	6.2	9.96	7.27	0.7	5.1	4.8
Aug.	3.94	72.2	6.1	9.38	6.77	0.7	4.7	4.0
Sep.	2.86	67.3	6.6	8.36	5.63	0.6	3.4	2.4
Oct.	2.70	56.5	7.5	7.86	4.44	0.5	2.2	1.7
Nov.	1.99	46.4	8.9	6.94	3.22	0.4	1.3	0.8
Dec.	3.00	39.3	9.2	6.83	2.68	0.4	1.1	0.6
Total or Mean	38.16	55.7	8.2	100.00	...	...	32.9	29.6

p = per cent of daytime hours for the year
$f = t \times p/100$ = monthly water use factor
k = monthly coefficient

[a] Computed by Blaney-Criddle formula $u = kf$ = potential evapotranspiration, inches (including interception).

[b] Estimate made by Penman.

TABLE 3 – *Computed normal monthly evapotranspiration for irrigated crops in the Piedmont area of North Carolina*

Month	Evapotranspiration, inches					
	Alfalfa	Grass pasture	Cotton	Peaches	Tomatoes	Tobacco
April	3.7	3.1	2.6	2.6	...	...
May	4.6	3.4	4.0	3.6	4.0	3.3
June	5.2	5.2	4.4	4.1	4.8	5.2
July	6.2	5.8	5.1	4.7	5.1	5.4
Aug.	5.8	5.4	4.3	4.0	...	3.6
Sep.	4.2	3.9	...	3.3	...	...
Oct.	3.3	2.9	...	2.4	...	...
Season	33.0	29.7	20.4	24.7	13.9	17.5

mating potential evapotranspiration to the Wagon Wheel Gap Watershed in Colorado gives satisfactory results. However, his conclusions on the Coweeta Watershed Study, North Carolina, are open to question.

Several years ago the writer inspected watersheds in the vicinity of Coweeta. According to *Hoover* [1944], "... natural vegetation is composed of deciduous trees with abundant shrubs and minor vegetation in this watershed." This vegetation has a maximum opportunity for transpiration on account of favorable climate and because the soil moisture seldom reaches the wilting point. Table 2 presents estimates of monthly evapotranspiration in this watershed based on the formula of *Blaney* and *Criddle* [1950] and temperature records at Asheville. The principal growing season in this area extends from April 15 to October 15. This formula has been used by the *Soil Conservation Service* [1951] in North Carolina to compute the monthly evapotranspiration and peak daily use rate by crops for designing sprinkler irrigation systems. Examples of computed monthly evapotranspiration for irrigated crops in the Piedmont area are shown in Table 3.

TABLE 4 – *Potential monthly transpiration in Cheshire and Kent*

Area	April	May	June	July	August	September	Total
	inch	inch	inch	inch	inch	inch	inch
Cheshire	2.10	3.00	3.50	3.50	3.05	1.75	16.90
Kent	2.00	3.25	4.00	4.05	3.30	1.80	18.40

Penman [1954] has calculated monthly potential transpiration in connection with an excellent report on the need for irrigation in England. The total potential transpiration for six summer months ranges from 16.90 inches in Cheshire to 18.40 inches in Kent with the distribution shown in Table 4. These values of potential (or maximum) water need of a green crop were calculated from standard meteorological observations by means of the equation $E + K = R_s(1 - r) - R_B$ described by Penman.

A procedure developed by Veihmeyer employing the difference in evaporation between white and black Livingston atmometers is being used by the *California Division of Water Resources* [1955] and the University of California to determine evapotranspiration. The consumptive use (evapotranspiration) is determined by the use of the equation $U = SD$, where U is the consumptive use in inches, S is the atmometer coefficient, and D is the difference in evaporation between the black and white atmometers in cubic centimeters. Coefficients for various crops were established by correlating evapotranspiration and atmometer measurements.

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H. G. WILM (State University of New York, College of Forestry, Syracuse, N. Y., received August 22, 1955)—In recent years several investigators have devised methods for estimating evaporation or evapotranspiration from land surfaces by means of equations which have a rational physical background and are adapted to reality by empirical coefficients. Such equations have been found useful to obtain approximations of potential or actual water 'losses' from land or water surfaces.

Penman describes an equation of this kind, with its background of assumptions and empirical adjustments. Then he employs this equation as a check on the results obtained in two American watershed experiments. When, in one case, his estimates disagree with the observed data, he infers that the data must be wrong, that unmeasured water leakage must have occurred from the watershed in question.

As the correctness of this inference is open to question, it seems appropriate to examine its background. Starting with a reasonable equation for estimating evaporation from a water surface, Penman obtains an estimate of 'potential transpiration' by applying empirical factors "f, having the values 0.6 for November to February, 0.8 for May to August, and 0.7 for the other four months. These values are for southeast England . . .

"The value of E_T so obtained is for a fresh green crop, of about the same color as grass, completely shading the ground, of fairly uniform height, and never short of water."

Applying his equation to the American watershed results, Pénman assumes that these coefficients with their restrictive limitations fit the following different American conditions: (1) a heterogeneous conifer-aspen forest in the Central Rocky Mountains, with a snowy winter climate and relatively dry summers; (2) a dense, mature hardwood forest of rough surface texture, on rugged mountain watersheds in the Appalachian Mountains, with a rainy, humid climate.

In his analysis of the Colorado data, Penman finds reasonably good agreement between his calculated estimates and the actual average difference between precipitation and runoff before the watersheds were cut-over. "On this evidence," he says, "there is no reason to question the watertightness of either of the test areas." But two accessory points need consideration: (1) that the original vegetation on the Wagon Wheel Gap watersheds was not uniform or dense enough to be comparable to a "fresh green crop . . . completely shading the ground"; (2) the summer showers in this area commonly do not meet the demands of evaporation and transpiration, so that deficits in soil moisture may occur repeatedly during the growing season. For these reasons, the observed figure of 15 inches per year is likely to be smaller than potential evapotranspiration by a complete canopy of vegetation.

Considering the Coweeta Watersheds, these particular areas were chosen with the greatest care, and every step in their control by precipitation and stream-flow stations was marked by efforts to insure the removal of biases such as water leakage into or out of each experimental watershed. Also, the voluminous and evenly distributed precipitation means that measured 'losses' are likely to approach 'potential evapotranspiration' very closely.

It would therefore seem that the principal difference between Penman's results and the observed data at Coweeta may not be water leakage, but more probably lies in his assumption that a "short green crop cover" can be compared to a dense, rough-textured hardwood forest. To illustrate this point, let us look at the results from another Coweeta Watershed. On the Carpenter Branch (Watershed 13) "all the woody vegetation . . . was cut down between September 1939 and January 1940 [*Kovner*, 1955]. ". . . the main characteristics of the treatment were the protection afforded the soil and the opportunity for sprout vegetation to take over the area. . . . rapid

protection to the soil was also provided immediately after cutting by the prompt establishment of a heavy sprout and brush cover in the first growing season after cutting in 1940." This heavy forest of sprouts has been allowed to grow without further cutting, so that now it forms a young, even-aged hardwood forest.

Before this treatment, the average annual water loss totalled 38.8 inches. For the first full hydrologic year after the treatment (1940–41), the losses totalled only 19.7 inches. Since then they have increased on a logarithmic curve, as might be expected from the increasing volume of the growing forest canopy. By 1945 the losses had risen to approximately 30 inches, and the trend was flattening off; and in 1952–53 they were about 34 inches.

Now the question may be raised: At what stage in the growth of this dense sprout forest could it be considered most comparable to the "short green crop cover, completely shading the ground?" Depending on the stage chosen, a person might suggest that there is leakage either into or out of the watershed.

But it certainly seems more logical to question the validity of the assumption that any full cover of vegetation will have identical evapotranspiration characteristics. On the contrary, evapotranspiration can be expected to vary with the volume of the canopy, its surface texture, and the volume and distribution of root systems.

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Kovner, Jacob L., Changes in stream-flow and vegetation characteristics, Ph.D. thesis, College of Forestry, State University of New York, June 1955.

H. L. Penman (Rothamsted Experimental Station, Harpenden, Herts., England; author's response)—I am grateful for Blaney's very kind remarks about Rothamsted; his was a most welcome visit. I have long been aware that my estimates of evaporation from cropped areas must eventually be brought into harmony with some of the very valuable data that he and his colleagues have collected. Blaney's Table 1 shows that we are not far apart when we are trying to estimate the same meteorological parameter.

Inspection of his publications shows, however, that we are rarely considering the same thing. Blaney and his fellow engineers have, very rightly and to our great benefit, measured the water use by irrigated crops under standard practice that leads to a satisfactory crop. I, as a physicist, am far behind, trying to determine the role of weather in transpiration when water supply is non-limiting, and when this condition is satisfied theoretical reasoning and such reliable relevant evidence as I have been able to find do suggest that weather is then dominant. Standard irrigation practice may, however, under-water or over-water for good reasons that have a sound basis in economics, soil management, or crop husbandry—or for the not-so-good reason that it is standard practice. An objective criterion is needed before criticism of standard practice can be attempted, and for me the first test is: Does the watering treatment meet the full requirement of the crop as estimated from weather data? To shorten discussion, consider only one possibility in the example quoted by Blaney. Assume that the alfalfa in California had all the water it could use, without excess lost by drainage; then 47 inches a year is an estimate of the potential transpiration. Is there any evidence to show that if the orange trees (with a maintained green crop on the ground between them) had been given the same watering treatment, then the total transpiration would have been only 24 inches? I doubt it; and would expect a value close to 47 inches.

Finally, a minor correction. The report referred to immediately after Blaney's Table 2 was a joint effort of agricultural and meteorological officers in Great Britain, and was published by the Ministry of Agriculture with R. T. Pearl as editor.

In reply to Wilm, our disagreement is primarily about the Coweeta data. Wilm says the particular areas were chosen with the greatest care. I believe this, and my whole case depends on my trust in the forester's and hydrologist's instinct that these two catchments were as nearly identical as could be found. But what is the objective test of identity? For me the major test of near identity is near equality in water balance, and this is a test that is completely independent of any theoretical formula or applicability of empirical constants. As I stated in my paper, the differences between rainfall and runoff quoted by Hoover were not equal: for Watershed 17 it was 42 inches per annum, for Watershed 18 it was 36 inches per annum. If these figures are true, the areas were not identical and not satisfactory for the test later imposed on them: if the areas were identical, the figures are not true. My choice is for the second alternative.

Since Wilm brings in unpublished data to support his case, perhaps I may be permitted to do likewise. E. A. Johnson of Coweeta has kindly sent me more records, and a map of the area showing the disposition of raingages. Each catchment had one gage in the valley, and one on the divide. I have not sufficient general knowledge of

raingaging, or particular knowledge of the Coweeta areas to be able to decide whether or not the network was close enough for "rugged mountain watersheds." Assuming that it was, there still remains a possible error of a few per cent in the individual gage readings. For the last ten years' data available to me (1944–1953), covering a period in which the cut area had recovered, the mean annual rainfalls and runoffs are: R_{17} = 76.9, r_{17} = 41.9, $(R - r)_{17}$ = 35.0 inches; R_{18} = 73.2, r_{18} = 39.9, $(R - r)_{18}$ = 33.3 inches. These values of $R - r$ are sufficiently close to each other to suggest that the equality of water balance is satisfied.

Using the Coweeta figures for the four years before cutting (Hoover used the rainfall for Watershed 17 for both catchments) the corresponding figures are: R_{17} = 69.6, r_{17} = 27.9, $(R - r)_{17}$ = 41.7 inches; R_{18} = 68.5, r_{18} = 34.1, $(R - r)_{18}$ = 34.4 inches. Is it not reasonable to ask why the value of $R - r$ for Watershed 17 was so very much greater during 1936–40, or to suggest that the test areas were suffering some major hydrologic inequality when the cutting of Watershed 17 was started? Add to this the sheer bad luck that the first important test year was by far the driest on record (the annual rainfall totals were only 51.3 and 49.7 inches for Watersheds 17 and 18), and it seems fair to repeat the suggestion in my paper, namely that the data and conclusions of Hoover's 1944 paper might be re-examined. I do not doubt that cutting on Watershed 17 increased runoff in the first year, but I would like to be sure that the main features of the water balance were not affected by hydrologic anomaly before the test, nor by very low rainfall during the test.

Finally, a word on the theoretical estimate. For many reasons my value of about 30 inches per year was expected to be an over-estimate of evaporation loss from a short crop cover; the effect of ventilation among trees is to increase the transpiration rate relative to a short cover, and hence the figure I gave might be expected to be about right because of compensation of errors. Considering the meager weather data I had to work with 'about right' means within ±15 pct in the annual average. Comparison with the later Coweeta values of $R - r$ suggests that there is no major error in the estimate; comparison with the earlier data still leaves a very big question mark against the rainfall and runoff data for Watershed 17. If that extra 7.3 inches of water per annum was evaporated where did the extra energy come from? If it did not evaporate where did the water go?

The Free Oscillations of Lake Wakatipu, New Zealand

G. A. BOTTOMLEY

Abstract—The period of vibration and the surface shape for the fundamental and several harmonics for free longitudinal oscillations have been deduced for Lake Wakatipu, New Zealand, from the behavior of a laboratory model similar to the Lake. The chief advantages of the model analysis as opposed to full algebraic treatment are the superior speed and the possibility of assessing the accuracy of the results by minor alterations in the original model.

Description of the Lake—The Lake is of glacial origin and is situated in the southern part of the South Island, somewhat east of the main chain of the Southern Alps, with a surface elevation of approximately 1020 ft and a depth of 1000–1200 ft over the greater part of its length. Its form is that of an irregular Z with each arm approximately 15 miles in length (see Fig. 1). For the purposes of this paper we have disregarded a minor extension of the Lake, the Frankton Arm, which is connected with the Lake only by a narrow, shallow channel.

Hydrodynamic considerations—We shall consider only longitudinal seiches. Let a transverse section be drawn across the Lake at any point. The area of the Lake from one end, arbitrarily selected, up to this transverse line is denoted by x, the length of the transverse by b, and the cross sectional area in the vertical plane by c. The product bc at a point corresponding to a given x is termed D_x.

The fundamental equation of motion for the type of oscillation we are considering may be written

$$\frac{d^2V}{dx^2} = -\frac{V}{D_x} \times \lambda \quad \cdots\cdots\cdots\cdots (1)$$

where V is the volume which has crossed this transverse section up to a given time t. The periods, nodes, and surface shape may be obtained from this expression by appropriate computation provided that D_x is known.

The normal curve defines the nature of the oscillations; all lakes with similar normal curves have similar behavior. It is constructed by drawing a smooth curve along the length of the lake at about the mid-width, describing normals to this curve at many points and evaluating the function D_x for each of these transverse lines. The plot of D_x against x is the *normal curve* for the lake.

Various attempts have been made [*Chrystal*, 1905ab; *Doodson*, 1920; *Bergsten*, 1926] to calculate the periods and nodal points for real lakes from the corresponding normal curve. There are two reasons why we have not followed any of the methods developed by the above workers. First, the normal curve for Lake Wakatipu is much more complex than for the lakes mentioned above. This is due to rapid fluctuations in breadth from place to place and not to depth variations which indeed are moderate. Second, the data available for the depths of Lake Wakatipu are not adequate for the construction of an extremely accurate normal curve. This would not be serious if it were easy to obtain from any one selected normal curve an assessment of the accuracy of the computed periods. The influence of any slight change in the normal curve can only be obtained by a major recalculation of the periods, and other values, and this seemed to us a serious defect of the processes so far used.

Present method in outline—We have determined the normal curve for Lake Wakatipu from the available data, constructed a scale model of a rectangular lake equivalent to the normal curve, generated the various modes of vibration of the model when filled with water, and scaled the results in accordance with $T \alpha L D^{0.5}$. The surface form has then been deduced for each mode of vibration in the manner described later.

Such a method has the advantage that minor adjustments in the model, equivalent for instance to variations in the depth or the original normal curve, may easily be made and the corresponding periods and nodal effects calculated with relatively little labor.

Determination of the normal curve for Lake Wakatipu—The only bathymetric survey of the Lake was done in 1902 [*Lucas*, 1904] and was presented in the form of a contour map. These results may be used as given, except for conversion to the cgs system, for it seems unlikely that any appreciable silting up has occurred since then, and indeed we have independent confirmation of some soundings (private communication from Miss V. H. Jolly, 1954).

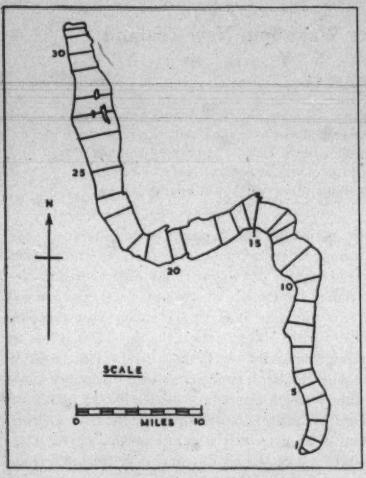

FIG. 1 – Lake Wakatipu, New Zealand

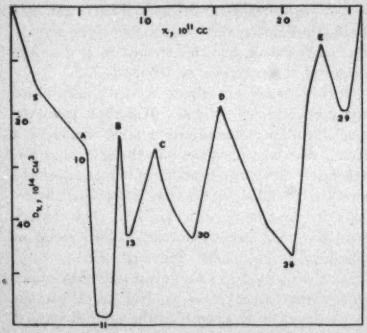

FIG. 2 – Relationship of D_x to x

The soundings in Lucas's work (194, distributed over the Lake's surface area of 112.3 sq mi) do not suffice to describe the lake contours as reliably as we would wish, but the position is helped materially by the uniformity of the depth and we have accepted Lucas's data as being adequate for the present purpose.

As shown in figure 1, thirty-two transverse sections were drawn on a copy of Lucas's bathymetric survey, scale 1:200,000, and the corresponding sections drawn on graph paper in enlarged form. The areas of the vertical sections and the areas to the transverse lines from the south end were evaluated by planimeter (or in some cases by square counting), combined with direct measurements of the transverse lines on the map, and the normal curve computed.

Figure 2 shows the smoothed curve of the function D_x against x for Lake Wakatipu. Assuming a constant breadth of 10^5 cm, the length of an equivalent rectangular lake becomes 259.0×10^5 cm, and the maximum depth 57.95×10^4 cm.

Construction of the model—The normal curve was laid out on a large sheet of graph paper so that the two extremes of the lake were 150 cm apart and the maximum depth 17.5 cm. The scaling factor for the time is thus

$$\frac{\text{Period of Lake}}{\text{Period of model}} = \frac{259.0 \times 10^5}{150} \times \left(\frac{17.5}{57.95 \times 10^4}\right)^{0.5} = 949$$

A sheet of 26 gage steel, 10 cm wide, was bent to the contours of the graph and clamped between two wooden boards and the model was glazed, painted, and leveled.

Determination of the periods for the model—As for the common pendulum the period is independent of the nature of the oscillating material and correspondingly the temperature of the water during measurements is without significance.

The seiches were readily generated in the model by forcing the water into oscillation by means of a bottle raised and lowered with roughly harmonic motion through the surface at a frequency which was varied until resonance occurred. With a little practice very smooth waves of the fundamental, the first, and second harmonic, and others, were obtained easily. The damping in the model (not related to the lake damping) was quite low and it was easy to follow up to 40 successive swings. The period for each of the modes was determined by timing twenty or more swings with a stop watch; errors of 0.2 second or more are not likely. After the bottle is withdrawn from the surface the inevitable splash waves soon die away, and the same is true for any higher harmonics which are unavoidably generated; no measurements were taken on seiches with such obvious defects. To avoid the possibility that the period depends slightly upon the amplitude we worked with displacements of less than one cm and usually less than 0.3 cm. Checking the period of a large amplitude wave as it underwent damping did not reveal any appreciable change in period.

The higher harmonics tended to be damped out

rather quickly for satisfactory timing. To avoid this trouble a gramophone motor was connected to a rough cross-head and plunger in the tank so that by careful regulation of the motor speed it was possible to generate and maintain waves of up to the seventh harmonic. There is some possibility that such forced seiches do not have quite the period appropriate to the model as such and we do not claim any great accuracy for these modes.

One curious feature was noted: there was no difficulty in generating any harmonic from one to seven, except the fourth which proved extremely intractable as the system would generally develop waves corresponding to the eighth harmonic. It is known that the location of a ventral point near a shallow part of the Lake may lead to an unstable system and this we presume is the explanation.

The nodes can be located by direct observation of the standing waves; no great accuracy is possible and we prefer the computational method given later. The results are shown in Table 1.

The periods of the fundamental and the harmonics do not form a series 1, 1/2, 1/3, 1/4, 1/5, . . . ; neither are the internodal distances uniform. These properties are inherent in the fundamental equation of motion for the seiche action; similar relations are to be found for the vibrations of a non-uniform stretched wire.

Probable accuracy of the deduced periods—Various adjustments to the model were made in order that the effect of errors in the normal curve might be estimated, and are summarised in Table 2. Note that the variations are of the sign and the order of magnitude predicted by $T \propto LD^{0.5}$.

With regard to the depth variation we remark that the errors in the bathymetric survey could scarcely lead to modifications as large as three mm. Correspondingly we claim an accuracy of about one minute on the period of the Lake.

The effect of reducing the volume of water in the deep parts of the Lake is remarkably small. A more accurate model of the Lake could be made without a full revision of the bathymetric data if the shallow parts were to be surveyed in a more detailed fashion.

The upper harmonics are very sensitive to the nature of the normal curve and some of the approximations in the theory will scarcely be satisfied for the higher modes. We have not made a detailed study of the effect of changes in the normal curve on any harmonic above the second, but we believe that the first two may be regarded as of only slightly less accuracy than the fundamental.

TABLE 1 – *Results of studies*

Harmonic	Model period	Lake period
	sec	min
Fundamental	3.22	50.9
First	1.75	27.7
Second	1.275	20.2
Third	1.00	15.83
Fourth	0.800	12.66
Fifth	0.700	11.08
Sixth	0.625	9.89

Calculation of the surface elevation for each oscillation mode—The elevation of the surface at a specific point of the Lake varies periodically with time and is directly proportional to the amplitude at a reference point such as one end, but it is not a linear function of the distance between the specific point and the reference point except in the case of the fundamental vibration for lakes of parabolic depth function and certain other specific cases.

The complete solution of the fundamental equation given only D_x is laborious, and has been done for very few lakes previously. We have circumvented the major part of the labor by utilising the values of λ which can be deduced from the corresponding period of oscillation of the model in its various modes to obtain V', which has the significance of being the elevation.

Consider as an example the determination of the surface elevation for the fundamental mode of the Lake. The surface elevation is of the same form for all lakes of similar hydrodynamic parameters, therefore it will suffice to calculate the elevation at various values of x for any model equivalent to Figure 2. To avoid some minor difficulties over units we shall consider a lake, divided into twenty equal areas, of length 20 cm, and of the same depth as our mechanical model. The fundamental period of this lake would be $20/150 \times 3.22$ sec, and the value of λ to correspond with this is 0.218 since $T = 2\pi/\sqrt{\lambda g}$. We must now solve the equation

TABLE 2 – *Adjustments made to study the effects on normal curve*

Adjustment	Time for 20 swings
	sec
Model unchanged	64.4
Water depth increased to 19 cm	62.2
Water depth decreased to 15.5 cm	70.5
Solid vertical partition at E	56.6
False floor across A–B	65.5
False floor across A–C	67.5
False floor across A–D	72.0

TABLE 3 – *Elements of calculation for fundamental model mode of model 20 cm long*

x	λ/D_x	V	V'	$-V''$
0	...	0	...	...
			1	
1	0.072560	1		0.072560
			0.92744	
2	0.04186	1.92744		0.08068
			0.84676	
3	0.03349	2.77420		0.92908
			0.75385	
4	...	...		...
			...	

$V'' = -(V/Dx) \times \lambda$, evaluate V at 0, 1, 2, 3, 4, ··· 20, and compute V'.

Both V and V' can be readily obtained by constructing a difference table in the following manner. First evaluate λ/D_x for all values 0, 1, ··· 20. At $x = 0$, $V = 0$, by the nature of the oscillations we are considering, and furthermore, we may set V' equal to any arbitrary value, say 1. These statements imply that $V_1 = 1$. But at $x = 1$ $V''_1 = -V_1 \times \lambda/D_x$ and thus the numerical value of V''_1 can be deduced. Similarly the second entry in the V' column is obtained by adding V''_1 to the first entry in V' column. The second entry in the V' column added to V_1 determines V_2. This process may be continued at will so that a table of V and V' is obtained for each point 0, 1, ··· 20. The sign of the entries varies as x increases, V' becoming negative and V reaching a maximum at a node; a rough sketch will ensure that no error is committed and is most desirable for the higher mode solutions. Table 3 shows the first few entries for the fundamental mode of the model 20 cm in length.

Our procedure is to compute V and V' in the above fashion from 0–15, and then similarly from 20–25 using the arbitrary assumption of V' equal to 1 at the second end. Now plot V against x for these two series. With the correct value of λ the curves should be parallel at the nodes but will not in general have equal ordinates. If the initial entry in the V' column is changed every entry in the V and V' column is diminished or augmented in the same ratio. The two series can be fitted together by multiplying the initial value for one series, and hence all the dependent quantities, by the ratio of the ordinates at a node. The final result is a tabulation of V and V' for the range 0–20.

Although we have used a 20 fold division of the Lake, at some increase in labor a more accurate result would have been obtained by a 50 or even 100 fold division. The limited accuracy of the lake survey does not warrant further numerical refinement. In the case of the second harmonic we have worked with a 40 fold division because the value of λ is sufficiently large to change V' at a rate which seemed to endanger the approximations. It was found that a slight adjustment of λ from that deduced from the second harmonic period was necessary in order to bring the two series parallel.

To avoid cumulative errors in the computation we have retained six significant figures in the operations, but, owing to the limited accuracy of the lake survey and the approximations used, the values of the elevations are not likely to be more precise than the second significant figure. An arithmetical error at any stage affects all subsequent stages so that it is important to check at intervals. This may easily be done by noting that the sum of the V'' (and the V') column equals the next entry in the V' (and the V) column.

Table 4 displays the calculated values of the elevation as a function of x for the first three nodes of vibration of the model. We have compared the calculated and the observed nodes and ventral positions on the model, but the observation errors are too large for accurate comparison, although the agreement is semi-quantitative. There is no satisfactory method of obtaining the surface shape from the model by direct observation.

TABLE 4—*Elevation in arbitrary units as function of position on model*

x	Fundamental	First harmonic	Second harmonic
0*	1.00	1.00	1.00
1	0.92	0.78	0.54
2	0.85	0.56	0.30
3	0.77	0.35	−0.02
4	0.67	0.12	−0.27
5	0.60	−0.05	−0.40
6	0.52	−0.18	−0.46
7	0.42	−0.32	−0.48
8	0.31	−0.44	−0.42
9	0.18	−0.55	−0.32
10	0.08	−0.60	−0.21
11	−0.06	−0.60	−0.05
12	−0.26	−0.54	+0.18
13	−0.45	−0.43	0.40
14	−0.57	−0.24	0.51
15	−0.61	−0.12	0.59
16	−0.72	−0.01	0.48
17	−0.82	0.20	0.25
18	−0.96	0.57	−0.39
19	−1.06	0.84	−0.78
20†	−1.10	0.97	−0.95

* South end.
† North end.

The actual values of the elevation call for little comment; the amplitude of the higher harmonics is greater at the ends than at the non-terminal ventral points but on the actual lake it may prove easier to study the higher harmonics free from the fundamental vibration by observations elsewhere than at the ends. Observations at (20–21) transverse line reduce the amplitude of the fundamental and second harmonic to about 0.05 of the end amplitudes so that such a site should be very favorable to the observation of a pure first harmonic. Similarly observation at 8–9 transverse or at 27 transverse should give relatively pure fundamental traces.

Comparison with lake-side observations—These calculations and experiments have been carried through to supplement a study of the Lake itself. The observations will be reported later, but it may at this stage be mentioned that the fundamental and the third harmonic are commonly seen in the actual complex wave form and that the period of the fundamental is in the region 50–55 minutes.

Further application of the model method—Many deep lakes show temperature stratification in the summer months. At the boundary between the upper warm and the lower cool water internal seiches may develop having periods long in comparison with the surface ones. The period of such seiches may be obtained from the model by filling it with suitable depths of two immiscible liquids and making the necessary calculation to refer to full scale lakes and the actual water densities observed.

Acknowledgments—The author wishes to recognise the material assistance given by R. McCraw in the construction and operation of the model, and the very considerable efforts of the staff of the University of Otago Library in obtaining references and texts from widely scattered and distant sources.

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The Progressive Lag of Sediment Concentration with Flood Waves

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Abstract—Numerous investigations of suspended-sediment discharge have shown that an increase in stream flow usually is accompanied by an increase in sediment concentration. The sediment-concentration peak during a rise may precede, coincide with, or follow the water-discharge peak. Observations on the Bighorn River in Wyoming and Montana show a progressive lag in peak concentration behind peak flow. The lag is most apparent when a single storm produces a flood wave that starts many miles upstream from the sampling sections.

Introduction—Anyone who has made investigations of suspended-sediment discharge has probably decided from preliminary results that normally there should be at least an empirical relationship between changes in sediment concentration and changes in rate of water discharge. Changes in rate of water discharge of any river cause changes in suspended-sediment discharge, and a given stream will normally carry a larger sediment load at a high stage than at a low one. A rapid increase in flow is usually accompanied by an immediate increase in sediment concentration, although during high stages the suspended-sediment concentration may vary over a very wide range and at any stage will seldom remain constant. These facts led to the commonly used method of computing daily records of suspended-sediment discharge, in which instantaneous sediment concentrations determined from samples collected at regular intervals are plotted on a print of a gage-height chart and a curve of sediment concentration is drawn, patterned after the shape of the daily gage-height trace.

The term 'flood wave' as used in this report does not imply an inundation overflowing the banks of the river; it is used synonymously with rise and refers to any rise and recession of flow resulting from surface runoff.

Results of other investigations—When enough data have been obtained to define the concentration changes, the results have indicated that the peak sediment concentration on any particular rise seldom occurs at the same time as the peak water discharge. On small streams the maximum sediment concentration usually occurs prior to the peak stage. *Johnson* [1943] noted that for certain streams the occurrence of maximum concentration depends on the stream discharge and is somewhat in advance of, or coincides with, the maximum discharge of the stream. *Benedict* [1948] noted for some typical examples, "that the peak sediment concentration may occur simultaneously with the peak of the water discharge (Medicine Creek at Cambridge, Nebr.) or as much as nearly four days in advance of the peak stage (Iowa River at Iowa City, Iowa)." This paper presents examples of midwestern streams wherein the concentrations progressively lag the flood waves.

The fact that the velocity of the sediment in suspension may be less than the velocity of the flood peak is not a new discovery. *Lewis* [1921] noted that during a flood in January, 1918, of the Tigris River at Amara, Iraq, the peak sediment concentration occurred three days after the peak discharge. At Baghdad, more than 350 miles upstream, the peak sediment concentration coincided with the peak of the flood wave. Lewis indicated that such an effect was possible only on rivers, such as the Tigris, that have a gentle slope; the slope of the Tigris in flood was about one foot in five miles. *Einstein* [1943] stated that the maximum discharge sometimes overtakes the maximum concentration, because changes in discharge travel with wave velocity, which is considerably higher than flow velocity for most streams.

Area of investigation—During 1947–53, four daily sediment sampling stations on the Bighorn River in Wyoming and Montana were operated by the Geological Survey. The relative positions of these stations are shown on Figure 1. One station was at Thermopolis, 35 miles upstream from Worland, Wyoming. The other stations were near Manderson, Wyoming, at Kane, Wyoming, and at Bighorn, Montana, and were about 14 miles, 69 miles, and 184 miles downstream from Worland, respectively. The sampling station at Bighorn, Montana, was about 3½ miles downstream from the stream-gaging station near Custer, Montana; however, the difference in location is insufficient to affect materially the subject phenomenon. Fifteenmile Creek, an ephemeral stream having a drainage area of about 500 sq mi, flows into the Bighorn River at Worland, and daily sediment sampling was started on this creek in 1951. The only tributaries of importance between Kane and Bighorn are the Shoshone and Little

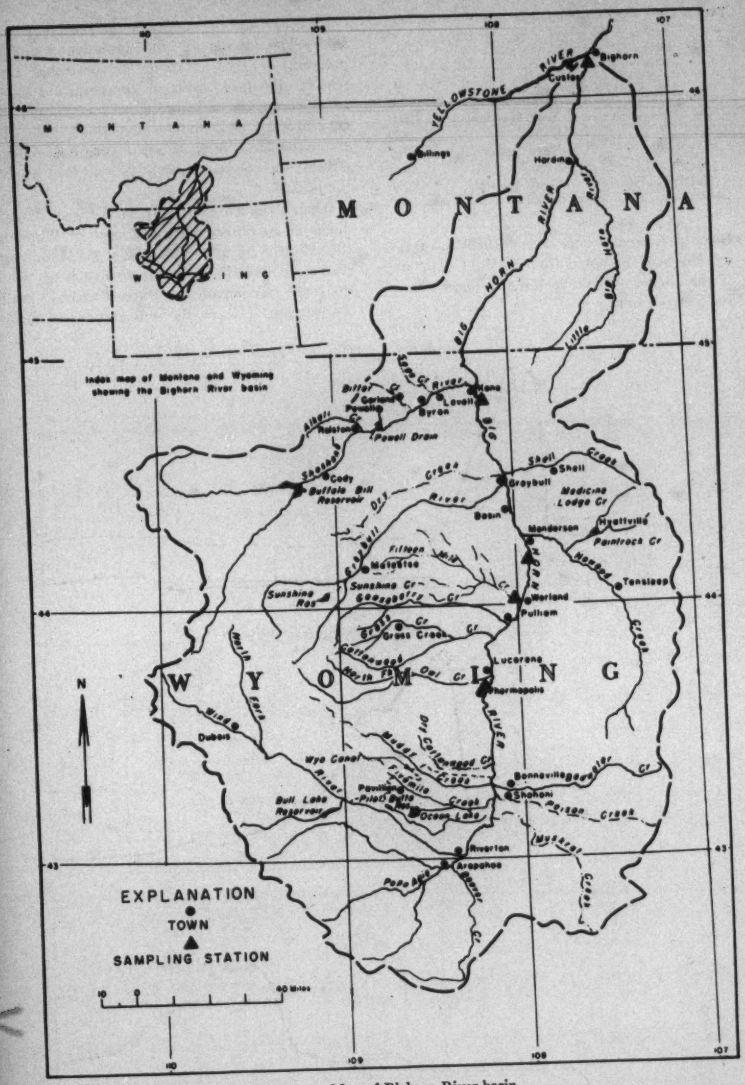
MONTANA
WYOMING
Index map of Montana and Wyoming showing the Bighorn River basin
EXPLANATION
TOWN
SAMPLING STATION
N
Bighorn
Custer
Billings
Hardin
Big Horn River
Yellowstone River
Little Big Horn
Basin
Greybull
Shell
Cody
Buffalo Bill Reservoir
Powell
Lovell
Byron
Garland
Thermopolis
Worland
Tensleep
Lucerne
Dubois
Wind River
Wyo Canal
Bull Lake Reservoir
Riverton
Arapahoe
Shoshoni
Bonnavilla
Pavillion
Pilot Butte
Ocean Lake
Meeteetse
Sunshine
Greybull River
Shell Creek
Medicine Lodge Cr
Hyattville
Paintrock Cr
Nowood
Fifteenmile Cr
Gooseberry Cr
Grass Creek
Owl Cr
Cottonwood
North Fork
Dry Cottonwood Cr
Muddy Creek
Owl Creek
Badwater Creek
Hamilton Dome
Little Wind River
Dry Creek
Popo Agie
Muddy Creek
Little Popo Agie
Bonnavilla Gulch
Shoshoni Canyon Creek
Wyo Canal
Pilot Butte
Ocean Lake
Riverton
Arapahoe

TABLE 1 – *Average discharges for water years 1946–52*

River	Station	Discharge
		cfs
Bighorn	Thermopolis	1708
	Near Manderson	1602
	Kane	2532
	Near Custer	4267
Shoshone	Byron	1062
Little Bighorn	Crow Agency	256

Bighorn Rivers. A measure of the size of these streams may be noted from Table 1. The slope of the Bighorn River at Kane is approximately five feet per mile.

Characteristics of sediment concentrations and loads—The results of the intensive sampling program at these stations demonstrated that whereas the peak sediment concentration sometimes occurs on or before a peak discharge, the concentration peak moves more slowly than the water discharge peak as a rise progresses downstream; the concentration peak soon lags behind the peak flow.

When a sudden rise transports a high sediment discharge on Fifteenmile Creek west of Worland, the sediment-concentration peak at the Manderson station is normally only one to five hours later than the accompanying water-discharge peak; downstream at Kane the sediment-concentration

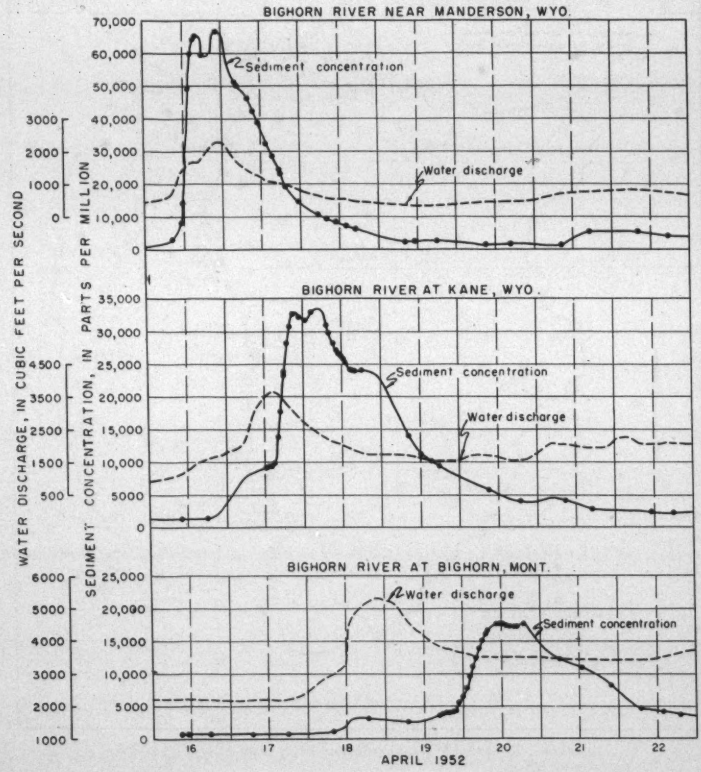

FIG. 2 – Discharge and sediment concentration of the Bighorn River, April 16–22, 1952

peak may be from 10 to 20 hr behind the peak water discharge. Still farther downstream at the station at Bighorn, Montana, the sediment-concentration peak is usually 30 to 40 hr behind the peak discharge, provided rain does not fall on the tributaries near or downstream from Kane. On April 15–16, 1952, a storm occurred on Fifteenmile Creek, and the changes with time of suspended-sediment concentration and water discharge were carefully determined for each station. Figure 2 illustrates the characteristic lag in peak sediment concentration on the Bighorn River.

The rise of April, 1952, is nearly ideal for illustrating the lagging concentration graph because it was due to a local storm on the drainage area of Fifteenmile Creek when the flow of the Bighorn River was low and because other agents that might have obscured the phenomenon were not present. Downstream tributary inflow that might cause a sudden increase in concentration

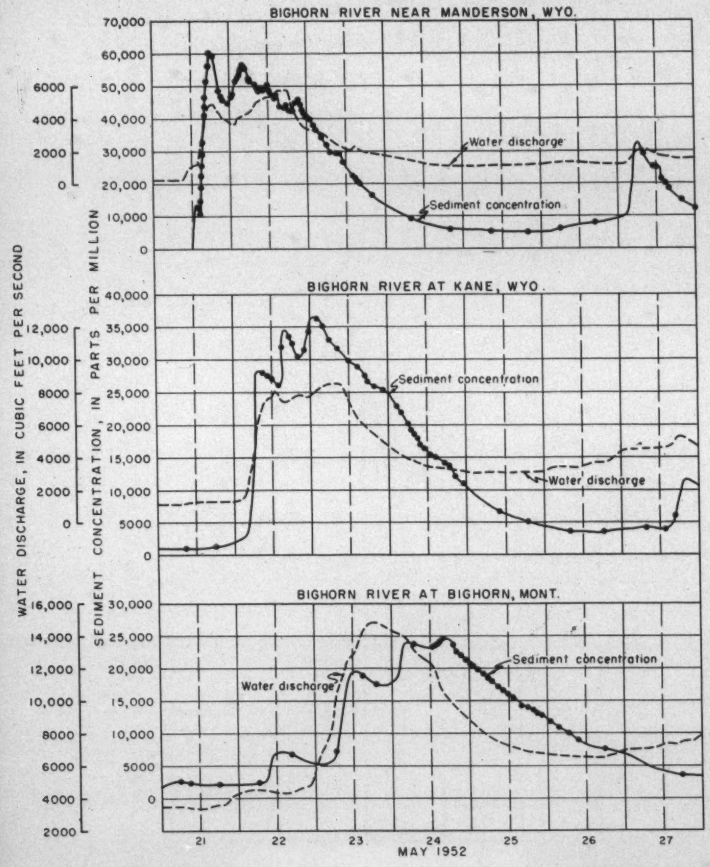

FIG. 3 – Discharge and sediment concentration of the Bighorn River, May 21–27, 1952

with little increase in stage did not enter the river. No overbank flooding occurred to slow the movement of the flood crest relative to flow velocities in the main channel. Also, bank caving that for some streams causes sudden increases in concentration did not occur. On the Bighorn River below Kane the channel is relatively stabilized, and bank erosion is negligible at normal stages or

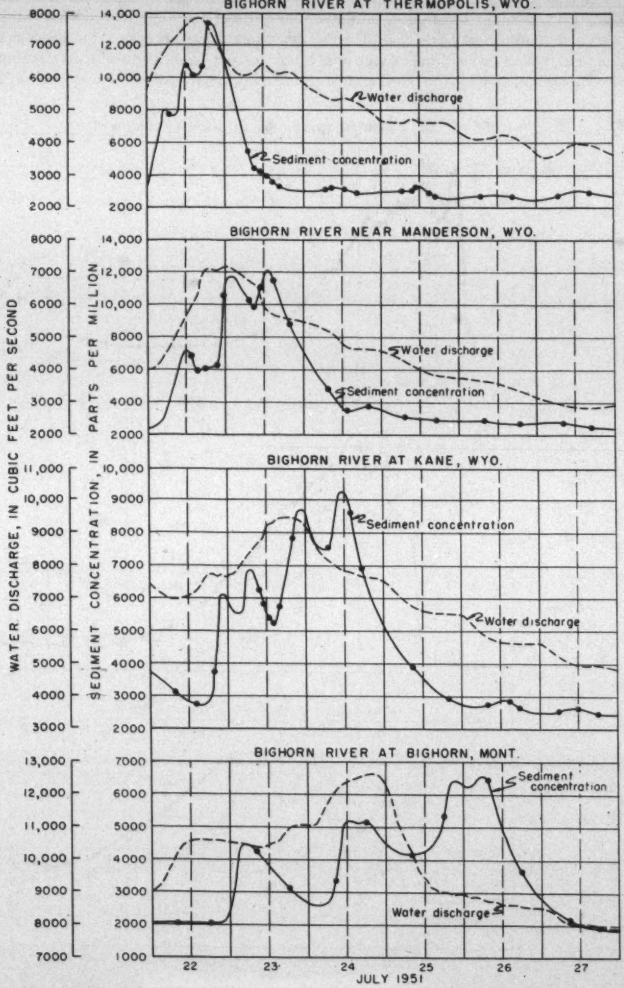

FIG. 4 – Discharge and sediment concentration of the Bighorn River, July 22–27, 1951

during occasional rises in flow. The percentage of the total suspended-sediment load originating in the river below Kane is small because the stream flows through a narrow deep canyon having older more resistant formations characteristic of a typically incised stream and, after emerging from the canyon about 65 miles upstream from the mouth, the stream flows across a gently sloping terrain, is close to grade, and has a wide stable-banked channel.

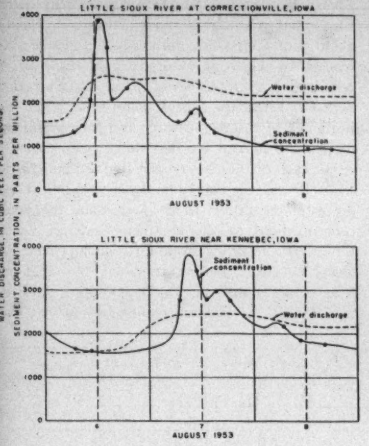

FIG. 5 – Discharge and sediment concentration of the Little Sioux River, August 6–8, 1953

Rains on various parts of the Bighorn River drainage area other than Fifteenmile Creek can carry additional sediment into the river and cause a lagging concentration. Figure 3 indicates how the concentration peak lagged behind the discharge peak from Manderson to Bighorn when general rains occurred on several tributaries of the Bighorn River during May 1952. On May 22 a peak discharge of 3300 cfs was attained on Fifteenmile Creek near Worland, Wyoming, but other tributaries likewise contributed substantially. For example, the peak discharge for the Greybull River near Basin was 3220 cfs on May 21, and the peak discharge at the Shoshone River at Byron, Wyoming, was 6530 cfs on May 22.

Figure 4 illustrates the lag that resulted when a rise originated upstream from Thermopolis, probably largely on the Fivemile Creek drainage area. On the basis of Figures 2, 3, and 4 and other observations during these investigations, it is believed that nearly all rises of the Bighorn River produce some lag in concentration. When a series of diurnal fluctuations occur, such as during spring

TABLE 2 – *Total suspended-sediment discharges during high-water periods*

Bighorn River station	Base flow (one day)			Period of rise			Total discharge for period of rise[a]		Discharge increase or decrease between main sections	
	Date	Discharge		Date	Discharge					
		Water	Sediment		Water	Total sediment	Water	Sediment	Water	Sediment
		cfs	tons/day		cfs day	ton	cfs day	ton	cfs day	ton
	1950			1950						
Thermopolis, Wyo.	Sep. 19	2,080	17,400	Sep. 20–23	11,560	505,900	3,240	436,300	...	...
Near Manderson, Wyo.	Sep. 19	2,070	21,600	Sep. 21–24	12,050	435,200	3,770	348,800	+530	−87,500
Kane, Wyo.	Sep. 20	2,780	19,400	Sep. 22–25	15,200	368,400	4,080	290,800	+310	−58,000
Bighorn, Mont.	Sep. 22	4,170	16,500	Sep. 23–26	19,150	252,000	2,470	186,000	−1,610	−104,800
	1951			1951						
Thermopolis, Wyo.	July 20	4,930	26,400	July 22–25	23,170	331,800	3,450	226,200	...	...
Near Manderson, Wyo.	July 20	3,910	28,000	July 22–25	20,760	361,700	5,120	249,700	+1,670	+23,500
Kane, Wyo.	July 20	6,240	41,400	July 22–25	30,850	472,400	5,890	306,800	+770	+57,100
Bighorn, Mont.	July 21	8,890	47,800	July 23–26	41,040	492,000	5,480	300,800	−410	−6,000
Near Manderson, Wyo.	Oct. 3	920	2,630	Oct. 4–12	16,500	270,980	8,220	247,310	...	...
Kane, Wyo.	Oct. 4	1,650	4,900	Oct. 5–13	23,390	257,560	8,540	213,460	+320	−33,850
Bighorn, Mont.	Oct. 5	3,040	4,440	Oct. 6–14	34,560	302,770	7,200	262,810	−1,340	+49,350
	1952			1952						
Near Manderson, Wyo.	Apr. 15	412	423	Apr. 16–21	4,588	335,630	2,116	333,092	...	...
Kane, Wyo.	Apr. 16	1,290	3,620	Apr. 17–22	12,300	376,700	4,560	354,980	+2,444	+21,888
Bighorn, Mont.	Apr. 17	2,240	4,720	Apr. 18–23	22,580	387,800	9,140	359,480	+4,580	+4,500
Near Manderson, Wyo.	May 20	232	276	May 21–26	12,370	1,081,000	10,978	1,079,344	...	...
Kane, Wyo.	May 20	1,200	3,370	May 21–26	24,660	1,297,140	17,460	1,276,920	+6,482	+197,576
Bighorn, Mont.	May 21	3,560	20,600	May 22–27	49,230	1,397,300	27,870	1,273,700	+10,410	−3,220

[a] Base flow deducted.

runoff, the lag of concentration peaks is difficult or impractical to detect; however, the concentration and water peaks are often out of phase with each other.

Sediment investigations of other streams in the United States have given further evidence that the lagging concentration is not limited to a few special streams under special conditions. A rise in sediment concentration appears to lag behind a rise in discharge sometimes on the Little Sioux River in Iowa (see Fig. 5). Many times, inflow between Correctionville and Kennebec contains high sediment concentrations and normally prevents the concentration lag from being evident. However, when the inflow originates mainly upstream from Correctionville, the graphs of the two stations are similar in shape and indicate the lag. As Kennebec is only about 30 miles downstream from Correctionville, the time that the concentration lags behind the discharge is not very much greater at the downstream station than at the upstream one. Concentration graphs have shown lags on such rivers as the Mississippi River at St. Louis, Missouri, and the North Platte River near Cassa, Wyoming. The flood waves on the North Platte River were caused by releases from Alcova Reservoir about 115 miles upstream from Cassa and resulted in sudden rises in stage of about four feet. Once the desired discharge was reached by release of water from the reservoir, it remained constant; the sediment concentration near Cassa reached a peak some 12 hr after the beginning of the rise in stage and then gradually dropped to normal for that flow.

For each of the rises on the Bighorn and Little Sioux Rivers, the maximum concentrations at the downstream station were lower than the peak concentrations at the upstream stations. On a typical rise resulting from Fifteenmile Creek inflow, the peak concentration on the Bighorn River near Manderson was 65,000 ppm. At Bighorn, Montana, the peak concentration was less

Date	Computed water discharge (acre-feet)	Computed load (tons)
April 17	4,440	4,720
April 18	7,720	23,500
April 19	8,510	39,400
April 20	7,060	150,000
April 21	6,900	105,000

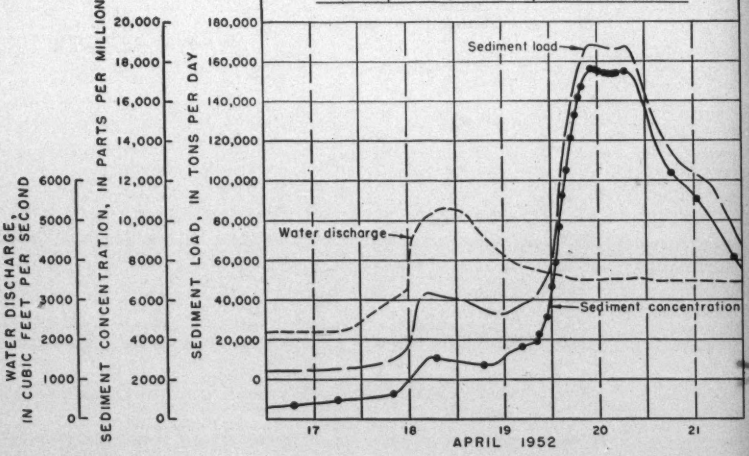

FIG. 6 – Discharge, sediment concentration, and sediment load measured on the Bighorn River at Bighorn, Mont., April 17–21, 1952

than 20,000 ppm. Although the peak concentrations are lower at the downstream stations, they remain above average for a longer period of time; a flattening effect on the concentration curve can be seen in Figure 2. Decreased maximum concentrations may be caused by dilution from the inflow of tributary streams. Because of the decrease of peak concentration, there may be conjecture

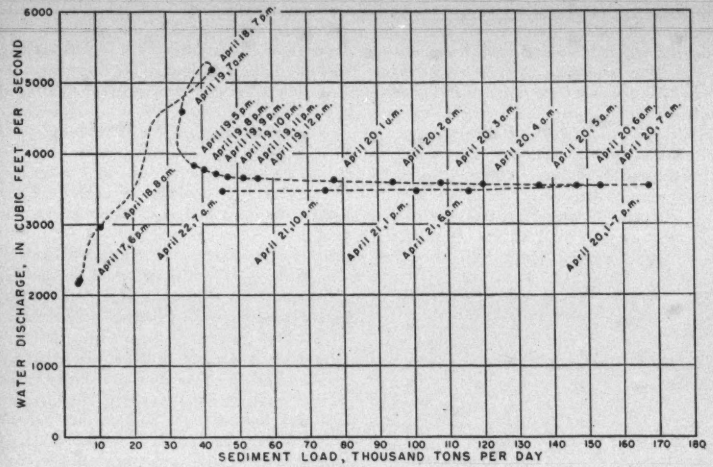
WATER DISCHARGE, IN CUBIC FEET PER SECOND
SEDIMENT LOAD, THOUSAND TONS PER DAY
April 18, 7 p.m.
April 19, 7 a.m.
April 19, 5 p.m.
April 19, 8 p.m.
April 19, 9 p.m.
April 19, 10 p.m.
April 19, 11 p.m.
April 19, 12 p.m.
April 20, 1 a.m.
April 20, 2 a.m.
April 20, 3 a.m.
April 20, 4 a.m.
April 20, 5 a.m.
April 20, 6 a.m.
April 20, 7 a.m.
April 18, 8 a.m.
April 17, 6 p.m.
April 22, 7 a.m.
April 21, 10 p.m.
April 21, 1 p.m.
April 21, 6 a.m.
April 20, 7 p.m.

FIG. 7 – Relation of water discharge to sediment discharge, Bighorn River at Bighorn, Mont., April 17–22, 1952

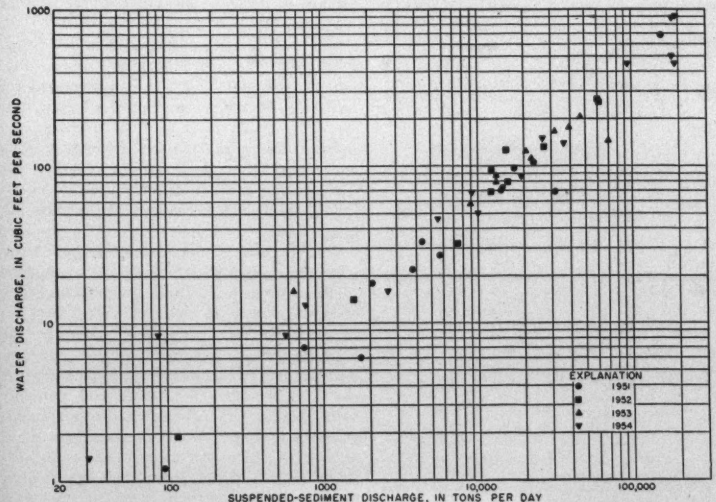

FIG. 8 – Relation of water discharge to sediment discharge, Fifteenmile Creek near Worland, Wyo.

about the possibility of deposition during the passage of the sediment load down the channel.

In order to show the changes in total quantity of suspended sediment passing the several sections, Table 2 was prepared from data obtained from five rises at various dates and periods when tributary inflow was relatively constant. The period for each rise included, insofar as possible, the time from the beginning of the rise until the river returned approximately to normal. For most rises observed on the Bighorn River the total suspended-sediment load was greater at each station than that at the one immediately upstream. The increase does not necessarily represent a lack of deposition, as the tributaries contributed a relatively constant flow and sediment load exclusive of the upstream stations. When the increase of the discharge and sediment load above the base flow is considered, the mixed results on Table 2 indicate some loss in sediment load between stations on some, but not on all, rises. These computations suggest that the deposition following these rises may not be significant; however, the results are somewhat inconclusive.

Sediment loads generally are more nearly in phase with concentration than with discharge. Figure 6 shows that most of the load passed the station when concentrations were high. This effect is often evident because the range of sediment concentration usually exceeds the range of water discharge. Note that the daily sediment load of 150,000 tons computed for April 20 is nearly four times the load for April 19, although the water discharge on April 20 is about 20 pct less than on April 19.

For each of the examples of lagging concentrations, including that of the Tigris River, the size of the particles in suspension was relatively fine. That is, most of the particles would be classified as wash load. In a recent paper *Chien* [1954] has restated that wash load is far less dependent on the water discharge than on its availability in the source areas. The points on a plot of instantaneous wash loads against water discharge may scatter because of variations in size of sediments and in storm intensities within the source areas. However, the scatter, sometimes at least, is far more dependent on the lag of concentration behind water discharge.

Figure 7, which is a plot of sediment load versus discharge for the Bighorn River at Bighorn, Montana, for the April, 1952, rise, is meaningless until interpreted by the phenomenon of a lagging concentration graph. Plots of water discharge and sediment load (Fig. 7) will be different in slope and shape for each flood wave and for each station; the difference will depend on the amount of lag, the flattening of concentration graphs, and other factors.

Channel runoff in the Fifteenmile Creek basin is usually over an initially dry bed that contains silt and clay as well as sand-size particles, all of which deposit in the channel during flood recessions. The channel slope is 11 ft/mi near the downstream end and more on the upstream reaches. The turbulence at the leading edge of the wave is sufficient to move and transport sediment, and at the Worland station the concentration peak usually precedes the discharge peak. A plot of suspended-sediment load versus discharge (Fig. 8) has less scatter than similar plots for most streams that have continuous flow, even

TABLE 3 – *Ratios of wave velocity to concentration velocity*

Reach	Distance	Date	Velocity		Ratio
			v_w[a]	v_c[b]	v_w/v_c
	mile		mi/hr	mi/hr	
Fifteenmile Creek near Worland, Wyo., to Bighorn River near Manderson, Wyo.	14	Oct. 5, 1951	2.3	1.2	1.9
		Apr. 16, 1952	2.3	1.1	2.1
		Average	2.3	1.2	1.9
Fifteenmile Creek near Worland, Wyo., to Bighorn River at Kane, Wyo.	69	Oct. 5–6, 1951	3.3	1.8	1.8
		Apr. 16–17,1952	2.2	1.6	1.4
		Average	2.7	1.7	1.6
Fifteenmile Creek near Worland., Wyo., to Bighorn River at Bighorn, Mont.	184	Oct. 5–8, 1951	3.4	2.1	1.6
		Apr. 16–20, 1952	3.1	1.8	1.7
		Average	3.2	2.0	1.6
Bighorn River near Manderson, Wyo., to Bighorn River at Kane, Wyo.	55	May 1, 1951	2.9	1.6	1.8
		Oct. 5–6, 1951	3.7	2.0	1.8
		Apr. 16–17, 1952	2.1	1.9	1.1
		July 30–31, 1953	2.2	2.1	1.0
		Average	2.7	1.9	1.4
Bighorn River near Manderson, Wyo., to Bighorn River at Bighorn, Mont.	170	May 1–4, 1951	3.6	2.0	1.8
		Oct. 5–8, 1951	3.5	2.3	1.5
		Apr. 16–20, 1952	2.3	1.9	1.7
		July 30–Aug. 4, 1953	2.8	1.6	1.8
		Average	3.3	2.0	1.6
Bighorn River at Kane, Wyo., to Bighorn River at Bighorn, Mont.	115	May 2–4, 1951	4.1	2.3	1.8
		Oct. 6–8, 1951	3.5	2.4	1.5
		Apr. 17–20, 1952	4.3	1.9	2.3
		July 31–Aug. 4, 1953	3.2	1.4	2.3
		Average	3.8	2.0	1.9

[a] v_w is the velocity of wave peak, determined by times at which it passed given stations.

[b] v_c is the velocity of concentration peak, determined by times at which it passed given stations.

though Fifteenmile Creek material is mostly wash load.

In streams where the particles in transport are predominantly bed-material load, the sediment load is more sensitive to discharge. Usually plots of bed-material load versus water discharge have much less scatter than plots of wash load versus water discharge. The stream channel and the banks are the immediate sources of bed-material load and readily supply particles when the discharge increases. These particles are mostly coarse and move by steps rather than traveling the length of the river more nearly in one continuous journey. Because of the relationships between the entrainment, transport, and deposition of particles of the bed-material sizes, the sediment-concentration curve of streams that have sandy beds should have a similar shape and coincide in time with

TABLE 4 – *Particle size of suspended sediment*

[Methods of analysis: B, bottom-withdrawal tube; C, chemically dispersed; M, mechanically dispersed; N, in native water; P, pipette; S, sieve; W, in distilled water]

Date	Time	Suspended sediment: Per cent finer than indicated size, in millimeters: 0.002	0.004	0.016	0.062	0.125	Methods of analysis	Concentration at time of sampling (ppm)	Discharge (cfs)	Sediment discharge (tons per day)	Specific conductance (micromhos at 25°C)	Flow conditions
Bighorn River near Manderson, Wyo.												
May 1, 1951	12:09 p.m.	51	62	82	97	...	SPWCM	55,700	1,540	240,000	1,050	Near peak concentration, 5 hours past peak flow.
Oct. 5	9:50 a.m.	...	21	41	78	94	SPWCM	7,530	1,730	35,200	972	At very start of rise.
Do	5:45 p.m.	44	55	78	94	...	SPWCM	42,500	2,820	336,000	1,160	5 hours past peak flow; about on peak concentration.
Oct. 6	11:45 a.m.	...	58	78	94	...	SPWCM	7,860	2,300	48,800	943	Recession, near end of rise.
Apr. 16, 1952	2:00 p.m.	...	56	78	94	...	SPWCM	50,400	1,690	238,000	1,210	Concentration rising, before peak flow.
Do	10:53 p.m.	...	54	74	93	...	SPWCM	67,800	2,320	440,000	1,050	Peak flow and concentration.
Apr. 17	12:35 p.m.	48	62	84	97	...	SPWCM	37,300	1,180	123,000	1,530	Falling flow and concentration.
Do	12:35 p.m.	6	6	88	97	...	SPNM	37,300	1,180	123,000	1,530	
Bighorn River at Kane, Wyo.												
May 2, 1951	3:22 p.m.	47	59	77	92	...	SPWCM	11,000	1,950	57,900	1,050	Start of concentration rise, 12 hours past peak flow.
Do	3:22 p.m.	1	2	83	97	...	SPNM	11,000	1,950	57,900	1,050	
Oct. 5	9:45 a.m.	27	29	44	56	67	BWCM	1,360	2,020	7,420	1,190	12 hours before start of rise in stage.
Apr. 17, 1952	12:40 p.m.	34	43	62	84	...	SPWCM	9,320	3,560	89,600	1,110	2 hours before peak flow; 10 hours before peak concentration.
Do	12:40 p.m.	1	2	62	85	...	SPNM	9,320	3,560	89,600	1,110	
Do	7:05 p.m.	...	64	86	94	...	SPWCM	28,300	3,310	253,000	1,110	Before peak concentration, past peak flow.
Apr. 18	9:40 a.m.	...	68	91	96	...	SPWCM	29,200	2,120	167,000	1,080	19 hours past peak flow; 6 hours past second peak concentration.
Bighorn River at Bighorn, Mont.												
May 4, 1951	6:00 p.m.	...	67	83	90	...	SPWCM	6,270	5,250	88,900	774	8 hours before peak concentration; 36 hours after peak flow.
May 5	5:00 p.m.	...	63	76	86	...	SPWCM	4,420	4,930	58,800	759	Recession, past peak flow and concentration.
Oct. 9	7:00 a.m.	...	70	89	91	95	SPWCM	11,800	4,160[a]	133,000	1,130	30 hours past peak flow; about 11 hours past peak concentration.
Apr. 19, 1952	5:35 p.m.	...	55	78	87	...	SPWCM	3,860	3,840	40,000	1,070	21 hours past peak flow, start of concentration rise.
Apr. 20	9:20 a.m.	1	1	93	97	...	SPNM	17,200	3,560	165,000	1,060	At peak concentration, 40 hours past peak flow.
Do	9:20 a.m.	57	72	93	97	...	SPWCM	17,200	3,560	165,000	1,060	
Do	4:50 p.m.	...	75	93	96	...	SPWCM	17,300	3,560	166,000	1,040	On second peak concentration.

[a] Mean daily discharge.

the flood hydrograph. One should be able to interpret, in a general way, the sizes of material in transport by a close study of the patterns of the concentration graphs.

Analysis of progressive lag—The lag of the peak concentration behind the peak water discharge conforms with a relationship observed by *Seddon* [1900] that flood waves travel at a greater rate than the mean water velocity of a stream. *Gilcrest* [1950, p. 644], by using Seddon's relation with the Chezy and Manning velocity equations, has shown that the ratio of the wave velocity, v_w, to the stream velocity, V, is approximately as follows:

Channel type	Ratio v_w/V Manning	Chezy
Triangular	1.33	1.25
Wide rectangular	1.67	1.50
Wide parabolic	1.44	1.33

Craya [1945] has presented diagrams depicting a flood wave that outruns the flow of water and absorbs the water in its path.

According to theories, sediment particles are transported at the velocity of the water. Therefore, the ratio of the velocity of wave peak, v_w, to the velocity of the sediment-concentration peak, v_c, should be approximately the same as the v_w/V ratio for each channel. Velocities and ratios of four separate rises on the Bighorn River are shown in Table 3. The ratios range from 1.0 to 2.3, and the average is in fair agreement with the computed v_w/V ratio.

High ratios were observed in sufficient number to indicate the ratio v_w/v_c may exceed the ratio v_w/V derived by Gilcrest. The observation may reflect the choice of flood peaks and concentration peaks for determining velocities; possibly the 'centers of mass' of flood volumes and sediment loads would be preferred parameters if volumes and loads remained unchanged throughout the reaches. The higher ratio may be due also to selective separation; that is, sediment concentrations usually are greater near the stream bed than at the surface, whereas the current velocity is greater near the surface. The finer the sediment particle sizes are, the more uniform the concentration curve in the vertical will become, and the closer the sediment and mean stream velocities should be. In the Bighorn River the sediment sizes transported were relatively fine; therefore, the concentration ranges are probably never excessive. Table 4 shows that the percentage of sand (coarser than 0.062 mm) is generally less than 20.

One additional observation is that mean velocities from discharge measurements at regular stations are not necessarily representative of a reach, and for the Bighorn River their use was impractical in determining v_w/V ratios. On April 3 and 4, 1952, mean velocities from current-meter measurements on the Bighorn River near Custer varied from 3.77 to 2.08 ft/sec for measured discharges of 3490 and 3280 cfs. The differences in measured velocities resulted largely from differences in the two measuring sections.

Conclusions—These investigations show that the progressive lag of the peak sediment concentration with respect to peak water discharge occurs often and in many river reaches. The lag has been noted particularly when the suspended sediment consists of wash load, and then it conforms with Seddon's observation that flood waves travel at a greater rate than the mean water velocity. When there is a lag, daily suspended-sediment loads are much more accurately determined from sediment samples collected at frequent intervals than by use of sediment rating curves. When using plots of sediment load versus discharge, one should investigate whether loads are associated with lagging concentrations.

Acknowledgments—Basic water-discharge data used in this paper were furnished by the Surface Water District Offices of the U. S. Geological Survey in Denver, Colorado, Helena, Montana, and Iowa City, Iowa. Basic sediment data were furnished by the Quality of Water Offices of the U. S. Geological Survey at Worland, Wyoming, and Lincoln, Nebraska.

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Relative Infiltration Rates of Burned and Unburned Upland Soils

V. H. Scott

Abstract—To increase the value of range land densely covered by brush, a number of management practices are being employed. One practice, clearing by the use of fire, has raised the question as to its effect on the infiltration capacity of the soil. Application of single-ring infiltrometers for determining relative infiltration rates of upland soils is discussed. Values of the relative infiltration rates for burned and unburned areas are presented. In all cases the burned soils had substantially higher rates following a fire. One year later the results were similar with one exception.

Introduction—Much of the ten million acres of brush-covered range land in California is so densely covered by vegetation that it has little or no value, particularly from the standpoint of livestock or agronomic production. In an attempt to increase the value of this land, certain range-management practices are being employed. The more important ones are grazing, burning, and mechanical manipulation of the vegetative cover. In some cases these practices have a profound influence on the hydrologic factors of runoff, erosion, infiltration, interception, and others. For any general conditions of a watershed it is rather difficult, and in some cases impossible, to distinguish or isolate the effect of one or another of these factors on the water regimen of the watershed. Their relationships are closely interrelated. Nevertheless tests and measurements involving a variety of methods and analyses are being developed and used by hydrologists to evaluate the quantitative relationships of these factors.

Literature review—One range-management practice which has provoked considerable speculation, observation, and research is that of burning and its effect on the infiltration capacity of the watershed. Results and conclusions reached vary as to its effect. *Rowe* [1941] in a study on small plots reported that changes produced by burning resulted in a reduction of 90 to 95 pct in the infiltration capacity of the soil. *Veihmeyer* and *Johnston* [1944] state that the infiltration capacity of the soil on burned plots was not impaired. *Burgy* and *Scott* [1952] performed a number of tests on several upland soils and found that no decrease in infiltration occurred.

There is considerable evidence presented by a number of workers [*Brown* and *Montgomery*, 1913; *Kamoshita*, 1937; *Kelly*, *Dore*, and *Brown*, 1931; *Puri* and *Asghar*, 1940; *Steenkamp*, 1928] that heating to high temperatures tends to destroy the colloidal properties of soil. This change may contribute to higher infiltration rates. From studies on the effect of sterilization on soil properties it is reported that changes in soil structure, largely increases in aggregation, have occurred when soil has been heated [*Martin* and *Aldrich*, 1952; *Screenivisan* and *Aurangabadkar*, 1940]. *Scott* and *Burgy* [in press] present data based on a laboratory study which indicates changes in aggregation occur when certain upland soils are heated to temperatures which would be reached during the burning of brush.

Procedure—In order to compare the relative infiltration rates of certain upland soils on which burning of brush has occurred, a study was made employing single-ring infiltrometers. It is recognized that the use and results obtained by these devices have certain definite limitations particularly from the standpoint of interpreting results and applying them to the water regimen of an entire watershed. Nevertheless, their use offers the solution to a number of problems involved in making relative infiltration measurements on range-land watersheds. These problems include rolling to rough and steep topography; inaccessible areas; dense vegetative cover, which is so thick that movement of personnel or equipment is virtually impossible; and limited water supply. Single-ring infiltrometers have been used very satisfactorily on cultivated agricultural soils to determine differences in soil structure and surface treatments [*Doneen* and *Henderson*, 1953]. Modification in the application of single-ring infiltrometers to upland soils is required as conditions encountered are different than those for the valley agricultural soils. The upland soils have much higher relative infiltration rates, have had no cultivation, have few surface cracks, and it is not feasible to wet or prime the soil prior to making an infiltration study.

The infiltrometers used in this study were single cylindrical metal shells, approximately six inches in diameter and 20 inches high. The procedure followed was to drive the infiltrometer into the

TABLE 1 – *Relative infiltration rates of burned and unburned upland soils*

County	Date	Fifteen minutes		One hour	
		Control	Burned	Control	Burned
		in/hr	in/hr	in/hr	in/hr
Napa	52	1.85 ± 0.37	2.34 ± 0.53	1.16 ± 0.21	1.47 ± 0.24
	53	5.28 ± 0.66	3.98 ± 1.10	3.95 ± 0.52	2.02 ± 0.49
Madera	52	14.71 ± 1.31	18.06 ± 1.45	7.18 ± 0.40	7.67 ± 0.65
	53	17.65 ± 0.84	19.36 ± 1.34	9.67 ± 0.30	8.79 ± 0.46
Mariposa	52	4.84 ± 0.94	13.73 ± 1.69	2.79 ± 0.43	4.86 ± 0.55
	53	14.35 ± 1.84	17.50 ± 1.66	6.34 ± 0.65	8.37 ± 0.60
Nevada	52	5.37 ± 0.72	14.06 ± 1.66	3.41 ± 0.32	6.69 ± 0.32
	53	6.66 ± 0.70	8.30 ± 0.82	4.59 ± 0.43	5.67 ± 0.43
Nevada	52	7.33 ± 0.57	24.06 ± 1.36	5.27 ± 0.31	9.34 ± 1.12
	53	6.51 ± 0.79	15.33 ± 0.58	4.80 ± 0.43	9.06 ± 0.30
Shasta	52	7.57 ± 0.96	9.26 ± 1.01	5.50 ± 0.56	5.96 ± 0.59
Madera	53	19.45 ± 1.11	21.01 ± 1.29	...	...

ground approximately one to two inches, and fill it with water. A portable disk inserted into the cylinder during the filling operation protected the soil surface and, in the case of the burned areas, the ash on the soil surface from being disturbed. The drop in the water surface was recorded by means of a hook gage and the relative infiltration rate computed.

The usual procedure was to test an area before a control burn then retest soon after the burn. In a few cases several days had elapsed before the burned area was tested. In other cases similar adjacent burned and unburned areas were tested simultaneously. In all cases the areas tested were selected without bias after careful examination indicated no detectable underlying differences and that conditions were considered the same.

Six areas were tested during the summer of 1952. Five of these areas were retested in 1953 and one new area was included. These areas were in five California counties; namely, Shasta, Nevada, Napa, Mariposa, and Madera. The soils represented six of the typical upland soils found on rangeland watersheds. These were Redding, Aiken, Sierra, Hugo, and Vista. The parent material of these soils include coarse-textured granitic, fine-textured basic igneous, consolidated sedimentary, and mixed alluvium rocks. The vegetative cover varied from almost pure stands to mixtures of chamise, ceanothus, manzanita, oak, and grass. There was also considerable difference in the density of cover. This factor was most influential in determining the intensity of heat during the burn and the amount of ash on the soil surface following the fire.

Rates of infiltration were determined for the first 15 minutes and one hour after water was added to the infiltrometers. In several cases the rates were so high that the infiltrometers would be dry before the end of the hour period. No effort was made to refill them once they were empty. Therefore, the figures used to calculate the rate at the end of the hour period were for only those cylinders which still had water in them at the end of the period.

In each burned and unburned area except one at least 24 infiltrometers were set and filled. Only ten were set in each area in the Shasta County study.

Results and discussion—Values of the relative infiltration rates of the burned and unburned areas for the 15-minute and one hour period are presented in Table 1. In this table the unburned area is denoted as the control. The values of the standard error follow each relative infiltration rate.

It will be noted in every case for the 1952 tests and the one in 1953 (Madera) the relative infiltration rates of the burned soils is higher than that of the unburned. In the two Nevada sites on Aiken and Sierra soils the difference amounts to more than ten inches per hour for the 15-minute rate and three to four inches per hour for the one hour rate. Of the five sites retested in 1953 the rates were higher on the burned areas in all cases for the first 15 minute period except in the Napa County site. The difference between the burned and unburned on the other sites was not as great after one year, yet there appeared to be no apparent decrease in the rates of the burned areas except in the case of the Napa site.

On the basis of the statistical analysis the differences were highly significant at the one per cent level in three of the cases (the two Nevada and Mariposa sites) for the 15-minute rate and in two (the Mariposa and first Nevada site) of the one hour rate for 1952. For the 1953 results one

case (the first Nevada site) showed a highly significant difference at the one per cent level for the 15-minute rate.

Reasons that can be advanced for the increase in the relative infiltration rates may be attributed to physical and to some extent chemical changes in the soil at the surface.

Summary—These data indicate that the effect of burning and the presence of ash did not render the soil of the burned areas impervious to water. In fact the difference between the relative infiltration rates as measured by the single-ring infiltrometers was in favor of the burned areas in all cases immediately following a fire and with only one exception one year later.

The results of study should be applied with caution to large watershed areas subjected to the range management practice of burning. Such questions as the stability of the physical and chemical changes, the effect of raindrop impact, surface-runoff effects, and the loss in vegetative cover and the resulting decrease in interception must be evaluated and integrated in the hydrologic study of watershed management.

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The Reeff Horizontal Seismograph and Its Calibration

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Abstract—A new horizontal seismograph, having high magnification and excellent initiation of phases, has recently been invented by Nicholas Reeff. The instrument consists of an inverted pendulum seismometer, an electrodynamical generating system, and galvanometric registration. Since the pendulum mass is less than seven kilograms, galvanometric reaction on the seismometer motion must be considered in the calibration procedure. For calibration, the first adjustment suggested by Eaton was applied. For the periods of the seismometer and galvanometer both equal to 1.92 sec, the damping of the galvanometer equal to 1.00, and the damping of the seismometer equal to 1.70, the peak magnification was determined to be 5050 at a period of 1.9 sec.

Introduction—A new horizontal seismograph, of which a perspective view is given in Figure 1, has recently been invented by Nicholas Reeff. The seismograms from this instrument evidence high magnification and good initiation of phases. The unique element of this new type of seismograph is the seismometer which is a flat-hinge supported, inverted pendulum analogous to the Lejay-Holweck gravimeter.

The various aspects of the construction, theory, and calibration of this type of seismograph will be considered. The calibration procedure used is a new method developed in theory by Eaton which considers galvanometer reaction on the motion of the seismometer.

Construction—The Reeff horizontal seismometer consists of a base frame which supports an inverted pendulum. The gallows-like base frame has a cylindrical magnet mounted where the rope would be attached were it a gallows. The magnet is held in place by a screw-clamp collar and is easily removable. The view in Figure 2 of the seismometer with the inverted pendulum removed shows the frame construction and magnet arrangement clearly. Directly beneath the magnet, on the base plate, is located a holder for the flat spring hinge which supports the inverted pendulum. A close-up view of the hinge system is seen in Figure 3.

The pendulum consists of a brass tube on top of which a flat plate is attached. Upon this, two solenoidal wire coils are mounted coaxial with the magnet and perpendicular to the plane of the flat spring hinge. The bubble level tube secured to the lower end of the brass tube is used to ascertain when the pendulum is vertical: three leg screws provide adjustment.

The period of the inverted pendulum is changed by varying any one or more of the four constants of the flat hinge: height, width, thickness, or material. Changing the length of the hinge requires vertical adjustment of the magnet: this has been provided where the magnet holder is attached to the base upright. The solenoidal coils are wound of 34 gage wire, contain about 21,000 turns each, and have a resistance of approximately 4400 ohms per coil. For this calibration, the coils were in parallel. The take-off leads pass through the brass tube to terminals on the upper hinge clamp.

A d'Arsonval type galvanometer is used for registration. The present calibration work used a General Electric portable-type galvanometer no. 32C233G10, having a free period of 1.92 sec and a sensitivity of 0.0078 microampere per division. Damping of the galvanometer is provided by the resistance of the seismometer and made critical by the addition of a shunt. Damping of the seismometer is done by inserting copper cylinders between the coils and the magnet (see Fig. 4). These are held in place by friction with the inner surfaces of the coils and the damping is varied by varying the depth of insertion.

For clamping the seismometer, a wooden yoke is slipped over the collar of the magnet and brass sleeves are inserted between the damping sleeves and the magnet, providing a friction lock.

The present instrument was built by Sprengnether Instrument Co., St. Louis, Mo.

Theory—Of the three systems composing the Reeff Horizontal Seismograph, mechanical, electrodynamical, and electrical, only the mechanical has not been previously treated in the literature. The inverted pendulum is analogous to the case of an axial strut vibrating under a compressional stress acting through a lever arm. As the author was unable to solve this case, an experimental approach was undertaken.

To determine if the system were linear, decay curves were recorded and the period versus the amplitude graphed. The results showed the amplitude to be slightly dependent on the period; for a

FIG. 1 – Reeff horizontal seismograph

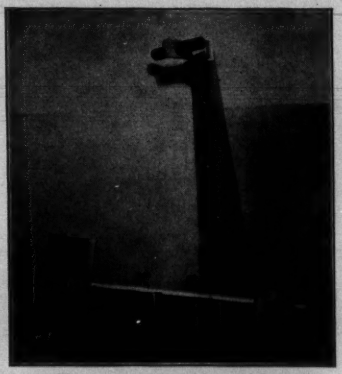

FIG. 2 – The seismometer with pendulum removed

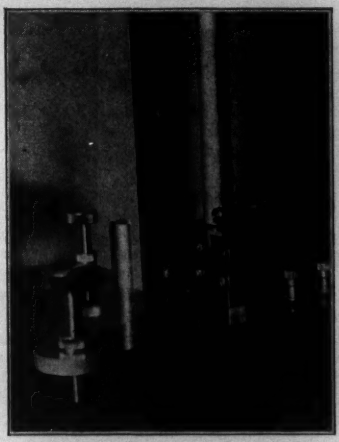

FIG. 3 – Close-up of hinge system of the seismometer

small range, however, the system could be approximated as linear. Since the motion caused by earthquakes is in a very small range, the system was treated as linear.

The differential equation of motion will be that of a linear rotational system with the inclusion of the astatization term due to the inversion of the pendulum, that is

$$K\varphi + (\tau - MgL)\,\varphi = N(t) \qquad (1)$$

where φ = angle of rotation from equilibrium
K = moment of inertia about axis of rotation
τ = torsional coefficient
M = mass of pendulum
g = acceleration of gravity
L = reduced pendulum length
$N(t)$ = driving torque

This equation has been derived neglecting higher order terms. Consideration of these terms and conditions for which they may be justifiably neglected are given by *Byerly* [1952]. All of the six conditions were satisfied for the Reeff Horizontal Seismometer by more than a factor of one thousand.

The electrodynamical generating system has been given a generalized vectorial treatment by *Antunes* [1950] and the special case of a uniform magnetic field has been developed by *Wenner* [1929]. Although the magnetic field of the Reeff horizontal seismograph is not uniform, the fact that the range of amplitudes of interest is very small allows the assumption that the field is effectively uniform. *Galitzin* [1911] has shown experimentally, and Wenner, theoretically, that when the mass of the pendulum is less than seven kilograms, the reaction of the galvanometer upon the motion of the seismometer must be considered. The mass of the pendulum of the Reeff horizontal seismometer is 2.4 kg and, therefore, galvanometer reaction must be considered.

Having shown the mechanical system to be effectively linear, the electrodynamical coefficient to be effectively constant, and the galvanometer re-

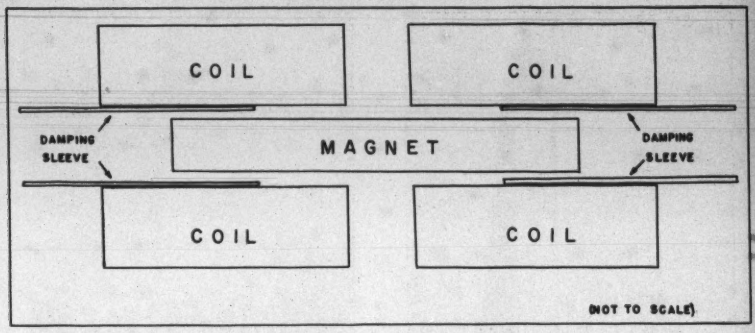

FIG. 4 – Cross-section of electrodynamical generating system

action to be significant, one may use the equations of motion of *Wenner* [1929, p. 977]. His restoring coefficient U will here be $(\tau - MgL)$ due to the addition of an astatization term.

Calibration—A review of the literature on the theory of the electromagnetic seismograph and its calibration has been given by *Eaton* [in press]. He, himself, has extended the theoretical work of *Coulomb* and *Grenet* [1935] for the conditions (equal periods or equal damping of the seismometer and galvanometer) permitting the general solution of the equations of motion. He finds the response of the system to several driving forces which are then used to develop calibration procedures. This method is based on the ratios of the damping and periods of the seismometer and galvanometer and has one of the ratios given, the other being determined by the instrumental constants. That is, to calibrate, one ratio adjustment is made, the constants of the system determined, the second ratio evaluated from the constants, and adjustment of the system to the second ratio made.

The calibration procedure which has been applied to the Reeff horizontal seismograph is the first adjustment suggested by Eaton. This arrangement has the seismometer overdamped and the galvanometer critically damped, with the free periods of the seismometer and galvanometer equal. For this case the proper damping of the seismometer is the factor evaluated from the instrumental constants.

As the Reeff horizontal seismograph was calibrated with the natural periods of the seismometer and galvanometer both equal to 1.92 sec, it was necessary to record all of the calibration measurements. Rough adjustment, however, could be made by eye.

The following adaptation of Eaton's first suggested adjustment was applied to the calibration of the Reeff horizontal seismograph.

Calibration procedure—(1) Determine the resistance r, the natural period T_g, and the critical damping resistance R_c, of the galvanometer by standard procedures [*Sohon*, 1932].

(2) Let the damping constant of the galvanometer be $\alpha = \alpha_0 + \alpha_1$ where α_0 is the portion of the damping independent of the current through the galvanometer, and α_1 is the portion dependent on the current. Record a decay curve of the galvanometer with open circuit; determine the natural logarithmic decrement δ_g from successive maxima or minima. The portion of the damping constant due to mechanical damping is

$$\alpha_0 \simeq \frac{\delta_g}{2\pi} \tag{2}$$

(3) Measure the resistance of the seismometer R, the mass of the seismometer pendulum M, and the reduced pendulum length L. A method of approximating the axis of rotation is given by *Graf* [1934].

(4) Compute the shunt resistance S, necessary to cause critical damping of the galvanometer by

$$S = \frac{RR_c}{R - R_c} \tag{3}$$

(5) For the desired critical damping $\alpha = 1$ and the portion of the damping constant due to the circuit is

$$\alpha_1 = \alpha - \alpha_0 = 1 - \alpha_0 \tag{4}$$

(6) Remove the damping sleeves and attach an equal nonmetalliferous mass at the same distance from the axis of rotation. Adjust the period of the

seismometer to that of the galvanometer and record a decay curve of the seismometer. *Do not remove magnet!* (The eddy currents which the magnet induces in the pendulum frame are a significant portion of the incidental damping.) Determine the logarithmic decrement δ_s, and compute the portion of the damping constant due to incidental damping β_0, by (2).

(7) Connect the seismometer to the shunt and either the clamped galvanometer or an equivalent resistance. Record a decay curve, determine the logarithmic decrement, δ, and compute the damping constant

$$\beta = \frac{\delta}{[4\pi^2 + \delta^2]^{\frac{1}{2}}} \tag{5}$$

β may be so large as to require the method of measuring large damping developed by Eaton [see also *Neumann*, 1954]. The portion of the damping constant due to the circuit is $\beta_1 = \beta - \beta_0$ as in (4) but $\beta \gtrsim 1$.

(8) From the values obtained for r, R, S, α_1, and β_1, compute the damping necessary to satisfy the first adjustment suggested by Eaton. (This is the conditional equation developed in the theory of the first adjustment.)

$$\beta_c = 1 + \alpha_1 \beta_1 \frac{S^2}{(r+S)(R+S)} \tag{6}$$

(9) Using the above data, compute the coupling factor, $\sigma^2 = \sigma_s \sigma_g$ where σ_s and σ_g are the seismometer and galvanometer transference factors, respectively. These are measures of the influence of the motion of each element of the seismograph upon the motion of the other element. The necessary formula is

$$\sigma^2 = \frac{\alpha_1 \beta_1}{\beta_c} \frac{S^2}{(r+S)(R+S)} \tag{7}$$

(10) Remove the weights attached in step 6 and replace the damping sleeves. Unclamp the galvanometer and insert the damping sleeves until the ratio of the first galvanometer maximum to the first galvanometer minimum $\left|\frac{\theta_1}{\theta_2}\right|$, prescribed by Plate I of Eaton for the above found value of β_c is obtained. Deflection of the galvanometer is caused by a light tap near the base of the seismometer pendulum.

(11) It is necessary to determine the ratio of the first galvanometer maximum to the initial deflection of the seismometer when the seismometer is released from an off-equilibrium position. The method of an addition of a small mass is used [see *Sohon*, p. 25]. Calculate the angular deflection of the seismometer $\varphi(t)$, in radians

$$\varphi(0) = x/d \tag{8}$$

where d is the height above the axis of rotation at which the small mass is placed, and x is the linear deflection caused by the mass. Remove the mass suddenly, thus giving the seismometer a release from off-equilibrium. From the amplitude of the first galvanometer maximum y (recorded amplitude), and the optical arm length L_T, the angular deflection of the galvanometer θ_1, is determined. The desired ratio $\left|\frac{\theta_1}{\varphi(0)}\right|$ is then computed.

(12) Obtain the factor $1/R'(\beta)$ corresponding to the value of $\left|\frac{\theta_1}{\theta_2}\right|$ obtained in step 10 from Plate I of Eaton. From these, compute the galvanometer transference factor.

$$\sigma_g = \left[\frac{\theta_1}{\varphi(0)}\right]\left[\frac{1}{R'(\beta)}\right] \tag{9}$$

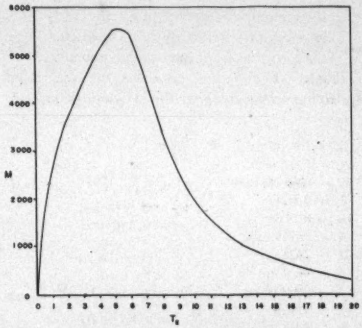

FIG. 5 – Magnification curve

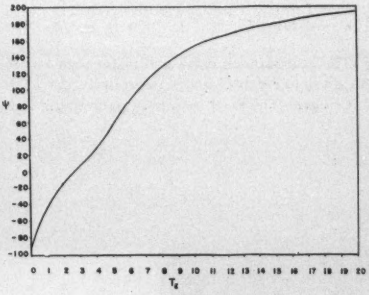

FIG. 6 – Phase-angle curve

(13) Compute the equivalent pendulum length.

$$l = \frac{gT^2}{4\pi^2} \tag{10}$$

(14) Measure the optical lever arm L to be used in actual operation of the seismograph.

(15) Compute the magnification and phase angle as functions of the angular frequency of the driving force with the formulas

$$M = \frac{2L\sigma_g\omega^3}{l\left[(\omega^2-1)^4 + 4\omega^2(\omega^2-1)^2 \cdot \left\{\frac{2-\sigma^4}{(1-\sigma^2)^2}\right\} + 16\omega^4\right]^{\frac{1}{2}}} \tag{11}$$

and

$$\psi = \tan^{-1}\left[\frac{(\omega^4 - 6\omega^2 + 1)(1-\sigma^2)}{2\omega(1-\omega^2)(2-\sigma^2)}\right] \tag{12}$$

respectively, where

$$\omega = \omega_e/\sqrt{\Omega_0\omega_0}$$

ω_e is angular frequency of Earth
Ω_0 is angular frequency of seismometer
ω_0 is angular frequency of galvanometer

Results—The values obtained for the Reeff horizontal seismograph by the above procedure are

$r = 188$ ohms	$\left\lvert\frac{\theta_1}{\theta_2}\right\rvert = 1.92$
$T_g = 1.92$ sec	$y = 12.3$ cm
$R_e = 1800$ ohms	$L_T = 143$ cm
$\delta_g = 0.021$	$\theta_1 = 0.0860$ rad
$\alpha_0 = 0.003$	$m = 0.430$ gm
$R = 2250$ ohms	$h = 3.5$ cm
$M = 2425$ gm	$x = 0.00128$ cm
$L = 44.4$ cm	$d = 54.6$ cm
$S = 9000$ ohms	$\varphi(0) = 2.35 \times 10^{-5}$ rad
$\alpha_1 = 0.997$	$\left\lvert\frac{\theta_1}{\varphi(0)}\right\rvert = 3.66 \times 10^3$
$\delta_e = 0.0592$	$1/R'(\beta) = 2.57$
$\beta_0 = 0.009$	$\sigma_e = 9.41 \times 10^3$
$\beta_1 = 0.835$	$l = 91.1$ cm
$\beta_e = 1.699$	$L = 100$ cm
$\sigma^2 = 0.494$	

The magnification curve and phase angle curve are given in Figures 5 and 6, respectively.

Critique—The Reeff horizontal seismograph is a very durable instrument and simple to operate. Because of its comparative inexpensiveness, it should stimulate the growth of the number of seismograph stations. The design of the Reeff horizontal seismograph has several modifications which are presently being investigated and developed. The difficulty of calibration may be reduced by making the mass of the pendulum sufficiently large so that the galvanometer reaction may be neglected.

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Volcanic Activity in Costa Rica and Nicaragua in 1954

FRED M. BULLARD

Abstract—The volcanic activity in Costa Rica in 1954 was limited chiefly to Irazú and Poás volcanoes, although fumarolic activity was reported at Rincon de la Vieja. The activity of Irazú is entirely fumarolic and of about the same intensity as in previous years. Volcano Poás, which had maintained a geyser-like activity from a lake which filled the bottom of the active crater for many years, began a new eruption in March or April, 1953. This, which appears to be a major eruption, is continuing with a large gas column frequently visible from San José and some fresh ash, cinders, and scoria on the upper slopes of the active cone. The volcanic activity in Nicaragua was limited to the following vents: (1) Concepción has been in a mild state of activity since 1948. The explosions, which sent out a cloud of gas, occur at intervals of about 30 minutes. (2) Santiago, which has been in a vigorous state of fumarolic activity since 1947, is continuing with some increase in the volume of gas and a corresponding increase in the area in which vegetation is being damaged. (3) Momotombo exhibited fumarolic activity at the summit crater in about the same intensity as in previous years. (4) Las Pilas began fumarolic activity in October, 1952, which has increased steadily in volume. The activity is localized along a fracture near the summit. (5) Cerro Negro contains some active fumaroles in the summit crater. (6) Telica has vigorous fumarolic activity in the summit crater in about the same intensity as in previous years. (7) El Viejo is reported to have some fumaroles in the crater but none were observed in a flight over it in a small plane.

Introduction—Central America, which is included in the circum-Pacific volcanic belt, contains one of the greatest concentrations of active volcanoes to be found anywhere (see Fig. 1). In addition to being the center of a great concentration of volcanic vents, Central America is one of the highly explosive volcanic regions of the Earth. *Sapper* [1927, p. 348] in an effort to compare the intensity of activity of various regions devised an index of explosiveness as follows:

$$\text{Index of explosiveness } (E) = \frac{\text{Quantity of incoherent material ejected}}{\text{Total ejected material}}$$

Sapper calculated the emission of volcanic material in the interval of 1500 to 1914. His estimate, notwithstanding the uncertainty of the figures for some areas, does give the order of magnitude and an overall view of recent active volcanoes. According to Sapper's figures the two areas tieing for first place with $E = 99$ pct are the Malayan Archipelago and Central America. Within a given region the distribution of volcanoes is irregular. In order to determine the most explosive areas, Sapper compared the ratio between quantity of fluid lava and fragmental material per 100 km of distance along the volcanic belt and concluded that the most explosive zone on Earth is in Nicaragua. Although Sapper's figures are open to question and are probably too high, as *Williams* [1952a, c] has shown, undoubtedly Central America, and Nicaragua in particular, is one of the most active volcanic belts on Earth.

NICARAGUA

Volcanic belt—The active volcanic cones starting with the Coseguina on the Gulf of Fonseca, extend in a southeasterly direction a distance of 150 miles to the island of Ometepec in Lake Nicaragua. This belt of some 40 cones and craters presents a striking sight which has impressed travelers in this part of the world since the time of the earliest Spanish explorers. Except for a small offset in the vicinity of Managua, the main chain of active or recently active volcanoes is almost straight. Along this line the volcanoes are grouped in clusters rather than being regularly spaced. At the northwest end of the chain, overlooking the Gulf of Fonseca, is the great cone of Coseguina. The violent eruption of Coseguina in 1835, which has recently been described by *Williams* [1952b] is one of the great volcanic eruptions of historic time. About 35 miles to the southeast is the Viejo group of cones, of which only Viejo has been active since the Spanish conquest. The Telica group, which represents the continuation of the belt along the Marabios Range, and in part overlaps the Viejo group, includes the active vent of Telica which has erupted intermittently since the time of the Spanish conquest and is currently in a brisk solfataric state. The extinct cones of the La Rota group come next, followed by the active Las Pilas group. Both Las Pilas and Cerro Negro have an eruptional history extending

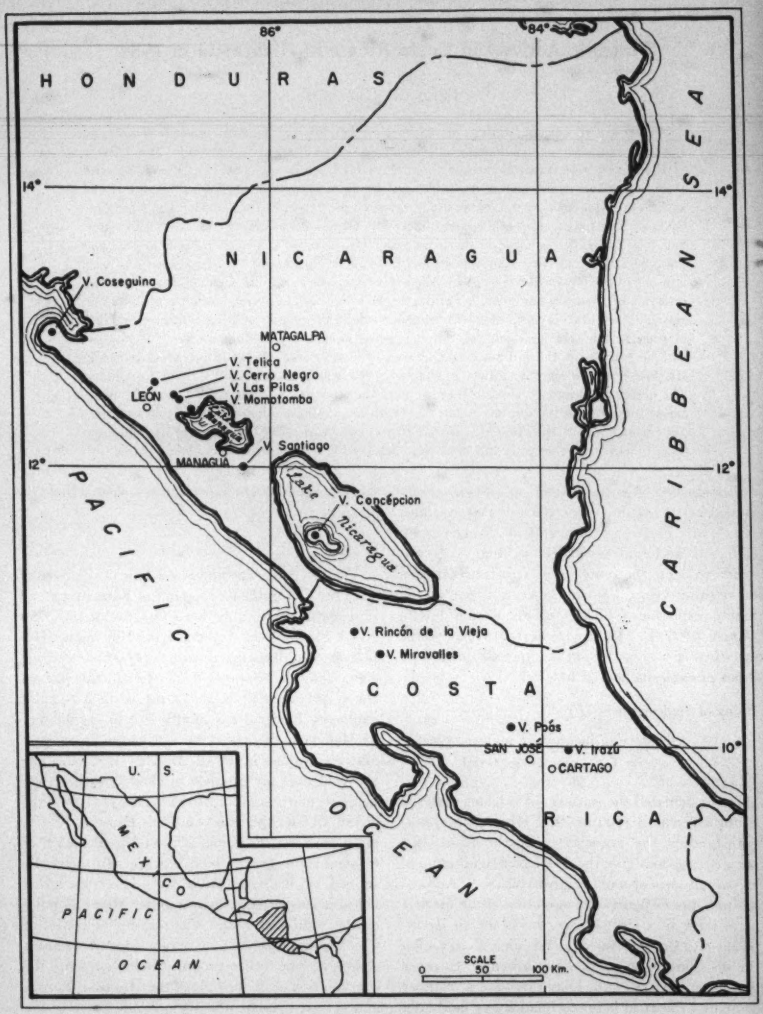

FIG. 1 – Location of active volcanoes in Costa Rica and Nicaragua

back for several centuries. Cerro Negro was in a vigorous eruption in 1947 in which a new cone was formed on the flank of the older group. Las Pilas is currently active. The next group, on the shore of Lake Managua, is dominated by the symmetrical cone of Momotombo which has erupted frequently during historic times. The next group of volcanoes includes the great caldera of Apoyeque and the adjacent but smaller Jiloa on Chiltepe Peninsula and the numerous pit craters and small cinder cones in

the Managua area. Many of these are the sites of attractive crater lakes such as Lake Asososca from which the city water supply of Managua is obtained. About 15 miles southeast of Managua and in almost perfect alignment with the volcanic chain lies the huge caldera of Masaya, which contains four principal vents, Santiago, San Pedro, Nindirí, and Masaya, of which the first is currently active. Next in line, and rising above the city of Granada on the shore of Lake Nicaragua, is the extinct cone of Mombacho. Last in the volcanic chain in Nicaragua are the spectacular cones of Concepción and Madera which join to form the Island of Ometepe in Lake Nicaragua. There are no records of eruptions of Madera but Concepción has been active at various times since the 18th century and is currently in eruption.

Volcanic activity in 1954—The activity, although largely solfataric, was widespread. The following vents were active as indicated:

Concepción—This cone, which is the larger of the two cones making up the Island of Ometepe in Lake Nicaragua, has been intermittently active since the 18th century. It has been in a mild state of activity since about 1948. The explosions occur at intervals of about 30 minutes and send out a gas cloud which at times is yellowish in color due to a small ash content.

Santiago—This is one of the four main vents which form overlapping lava cones within the great caldera of Masaya. When the Spaniards first visited the area two of the vents, Santiago and probably Masaya, were filled with a lake of fluid lava similar to the 'fire pit' of Halemanumau at Kilauea, Hawaii. The lava lakes disappeared about the beginning of the 17th century and thereafter there were numerous lava flows and strong ash eruptions from the Volcano. The lava flow of 1670 which spilled over the rim of the crater and the flow of 1772 are noteworthy. During the early half of the 19th century the Volcano was quiescent with only weak fumarolic activity. Strong ash eruptions occurred in 1858 and 1859 at which time the present outlines of the crater were established. In 1919 eruptions of fumes and ash from Santiago crater began to cause extensive damage to vegetation in the surrounding area. In 1927 two German engineers, in an effort to stop the fume damage, devised a plan to capture the gases and extract the sulphur on a commercial basis. Blasting on the rim and floor of the crater caused the main portion of the floor to collapse to a depth of 120 m below its former level, and the emission of fumes ceased altogether [*Schonberg*, 1927]. There was no renewal of fumes until 1946, and since 1947 it has continually emitted a column of sulphurous gases which have caused extensive damage to the coffee plantations to the southwest of the volcano.

FIG. 2 – Fissure cutting across the crest of Las Pilas Volcano, Nicaragua, Aug. 16, 1954

FIG. 3 - Crater of Telica Volcano, Nicaragua, Aug. 16, 1954

Momotombo—Rising from the shore of Lake Managua, across the Lake from the city of Managua, the symmetrical cone of Momotombo is a familiar landmark to all who have traveled in the area. Momotombo has erupted frequently in historic times, the last important lava flow being in 1905. Since that time it has frequently ejected ash and scoria and is almost always giving off an abundant column of gases. The activity in 1954 consisted of brisk solfataric activity from the summit crater.

Las Pilas—Situated in the Las Pilas–Cerro Negro group, this volcano has erupted several times in the past centuries but had been quiescent for many years. The present activity began in October, 1952, with the opening of a crack more than one-half mile in length cutting across the top of the cone beside the old crater (Fig. 2). The sides of the crack are coated with a white sublimate. Showers of ash erupted from the crack and fell in the area around León. The activity ceased in December, but in February, 1953, it began again from localized spots along the fracture. The active vent, a circular hole from which abundant bluish and white gas issues, is midway along the fissure and a short distance from the crest on the south slope of the mountain. No explosions were observed but the volume of gas has been steadily increasing and it is now clearly visible from Managua.

Cerro Negro—A vigorous eruption in 1947 resulted in a new cinder cone and some short lava flows. Ash was spread over a wide area causing considerable crop damage in the León area. In 1954 there was still some weak fumarolic activity at the summit crater and a few 'hot spots' in the lava flows near the base of the cone on the north side.

Telica—This volcano, which has erupted lava and ash intermittently since the 16th century, is in a brisk state of solfataric activity (Fig. 3). In fact, Telica has been in its present state of activity since the eruption of 1941.

El Viejo—Altough El Viejo is listed as currently active, and fumarolic activity is reported in the crater, no gases could be seen in a flight over the crater in a small plane.

COSTA RICA

Volcanic belt—In its broadest aspects Costa Rica consists of two mountain systems which form the backbone of the country, the volcanic range to the north and the Cordillera de Talamanca to the south. The volcanic range consists of a northern part, the Cordillera del Guanacaste, and the central part, the Cordillera Central. The Cordillera del Guanacaste consists of a series of volcanic centers, which range from 4500 to 6500 ft in elevation. From north to south these volcanoes are: Orosí (6106 ft), Rincón de la Vieja (5372 ft), Miravalles (6500 ft), Tenorio (6240 ft), and Arenal (4946 ft). These volcanoes are more or less aligned and

evenly spaced over a distance of about 45 miles. The Cordillera Central is much the higher and includes four major volcanic centers: Poás (8846 ft) on the north, Barba (9445 ft) in the center, and Irazú (11,154 ft) and Turrialba (10,816 ft) on the south.

The Cordillera de Talamanca, which includes the highest peak in Costa Rica (Chirripó Grande, 12,415 ft), is situated about 15 miles south of the Cordillera Central and extends from the vicinity of San José to the Panamanian border. The Cordillera de Talamanca is older than the mountains to the north, consisting of sharply folded Tertiary sediments and igneous intrusions. Doubtless it may have been the site of volcanic activity but erosion has long since destroyed cones which may have existed.

The Meseta Central which lies between the Cordillera de Talamanca on the south and the Cordillera Central on the north, is an intermontane basin between 3000 and 4000 ft in elevation. It is the area in which San José, Cartago, and the more important cities of Costa Rica are located.

Volcanic activity in 1954—The most active volcanoes were in the Cordillera Central, overlooking the city of San José, with minor solfataric activity in several of the volcanoes of the Cordillera del Guanacaste to the northwest. The following vents were active as indicated:

Orosí—The northernmost of the volcanoes of Costa Rica is Orosí, near the Nicaraguan boundary overlooking Lake Nicaragua. Orosí is reported to have a gas column rising from the crater but poor visibility prevented the writer from making any observations on three flights over the area.

Rincón de la Vieja—This volcano is regarded by experienced observers as the most active volcano in the Cordillera del Guanacaste. It is difficult to reach on the ground but is visited a few times each year by mountain-climbing parties. There is considerable fumarolic activity in the summit crater and also hot springs and fumaroles well down on the slope. Parties visiting the crater during the year report no significant change in activity.

Miravalles—The activity is limited to fumaroles and hot springs near the base of the cone.

Poás—The northernmost volcano of the Cordillera Central, with an elevation of 8846 ft, Poás overlooks the Meseta Central and the city of San José. As viewed from San José, it appears as a dome-like mass surmounted by a wide and obtuse cone marking the summit crater. The lower part of the Volcano is broken and cut by many canyons. A paved road reaches a point about three miles from the rim of the crater. A dense forest covers the slopes, extending to the rim of the summit crater. The summit consists of a series of intersecting craters in which at least three can be recognized. The southernmost crater, which is also the highest, is a well-preserved basin containing a beautiful lake of clear, cold water. Approximately one-fourth mile to the north is the active crater, the floor of which is approximately 900 ft below the level of the upper lake. The crater is surrounded by almost vertical walls which rise about 300 to 500 ft above the floor. The highest part of the rim is on the south.

Since early authentic records, especially since 1838, Poás has contained a hot, sulphurous, crater lake which at intervals erupted a geyser-like column of muddy water and steam. These geyser-like eruptions have been described by numerous writers, including *Alfaro* [1910], *Pittier* [1890], *Sapper* [1925], and by *Tristán* [1916] on numerous visits between 1904 and 1930. *Jaggar* [1931] and *Schaufelberger* [1931] and more recently *Stocking* [1946] have described the crater. Eruptions in 1910 and 1915–16 are especially noteworthy. From published descriptions it appears that there are two points on the surface of the crater lake, one at the south and one at the north, at which the water appeared to boil continuously. At the north location geyser-like eruptions of water and steam occurred at irregular intervals with a height and duration varying according to the degree of activity of the Volcano. The interval varied from as little as ten minutes up to one to four eruptions per day with the height ranging up to 1500 ft or more. In the great eruption of 1910, according to *Tristán* [1916], the column of water accompanied by ash reached a height of over 12,000 ft, then spreading out in a great umbrella shape, finally reaching a maximum height of 25,000 ft. Ash fell over the countryside and in the crater there were many bombs and scoriaceous fragments. In recent years Poás has maintained its geyser-like activity from the lake in the active crater.

A new eruption, which must be classified as a major eruption, began in March or April, 1953. The geyser eruptions became more vigorous, filling the entire crater with steam and covering the crater floor and walls with a layer of mud mixed with fragments of earlier rocks from the walls of the conduit. The eruption of fresh cinders began in mid-July and lasted for many days with variable intensity. The large gray eruption cloud, clearly visible from San José, rose to a height of about 3500 ft above the crater rim, expanding to the west in separate columns. Flashes of lightning in the cloud as well as a reddish glow were reported by nearby inhabitants. A layer of black cinders was deposited

around the upper rim of the crater and over the countryside to the west of the crater.

On November 10, 1953, the eruption was particularly violent, throwing out a large quantity of pyroclastic material. Black scoria, and bomb-like fragments as large as a man's head are abundant at the crater rim from this activity. Fragments the size of an egg were found a mile from the crater and some debris was noticeable three miles distant. Local inhabitants reported a spectacular 'fireworks' with lightning flashes and cannon-like explosions followed by a hail of 'incandescent rocks' on the night of November 10. As a result of this type of activity, a cinder and scoria cone has been built in the bottom of the crater in the space formerly occupied by the lake (see Fig. 4). When observed in August, 1954, the cone was estimated to be 70 to 100 ft high and the opening at the top of the cone was one of the most active vents in the crater. Abundant gas (appeared to be steam) accompanied by rocks was ejected at frequent intervals. The impact of the rocks falling on the cone and rolling down the side could be heard clearly from the rim of the crater. No 'red glow' of any type could be detected. In addition to the vent in the top of the cinder cone, there were two other vents. One was on the side of the new inner cone. It appeared to be about ten feet in diameter and at intervals large quantities of white vapor boiled out. The third vent, which was behind the cone and not clearly visible from the crater rim, emitted a bluish, more transparent gas. Occasionally a brownish, cauliflower eruption cloud was emitted from the vent in the top of the cone. Such eruptions are a daily occurrence and form an eruption cloud which can be seen from San José. The volume of gas continues to be large and local observers (airline pilots) believe that the fumes are becoming more pronounced. In flying along the valley, on the downwind side about ten miles from Poás, a distinct odor could be detected, similar to that at Santiago in Nicaragua. However, no vegetation damage has been reported except in the immediate vicinity of the crater.

Irazú—The cone of Irazú (11,154 ft) which merges with that of Turrialba (10,816 ft) forms the southeast end and the highest part of the Cordillera Central. Irazú is not only the highest but also the most accessible volcano in Costa Rica, since the rim of the crater is reached by a paved road. The early eruptional history of Irazú is somewhat in doubt since it was frequently confused with the nearby, now inactive, Turrialba, which was particularly active during the 19th century. One of the earliest recorded major eruptions of Irazú was in 1723 when large amounts of scoria and ash were

FIG. 4 – Active crater of Poás Volcano, Costa Rica, showing cinder cone being formed in the current eruption; lake in lower left is in an old crater; Aug. 27, 1954

FIG. 5 – Crater of Irazú Volcano, Costa Rica, Sep. 1, 1954

FIG. 6 – Crater of Irazú Volcano, Costa Rica; Sep. 1, 1954; the arrow identifies the reference point in Fig. 5

ejected. One of the largest ash eruptions from Irazú was in 1917 which caused considerable damage to the crops in the surrounding area.

Irazú is a complex volcanic mass with a number of old, overlapping craters at the summit. There are several levels in the crater (Fig. 5 and 6). The first level or outer crater forms a wide terrace (Playa Hermosa) around the south margin of the

present crater. This terrace, which is estimated to be some 300 ft below the outer rim, ends at the edge of the inner, active crater. From the edge of the terrace one looks into the inner crater where 500 feet below there are three prominent vents, two of which are pouring out columns of steam, while the third is inactive (Fig. 5). To the north of the active vents there is a shallow lake, largely filled by alluvium washed in from the sides of the crater. To the east of the inner crater and separated from it by a narrow knife-like ridge is an old crater which frequently contains a small lake.

Large columns of steam issue from the two active vents on the floor of the inner crater. There is no noise of any character and the steam seems to come in waves. An abundant outpouring for a few minutes was followed by a decrease to the point that it was possible to see into the vent, then another huge volume for five to ten minutes followed by another lull. The gas column was white and had a strong sulphur dioxide odor. Abundant deposits of a yellow (sulphur) sublimate coated the lower portions of the vents. The central vent, which gave out the largest volume of gases, has a pool of greenish water at the bottom. In the brief lull between the waves of steam a yellow scum, which was assumed to be sulphur, could be seen floating on the surface of the water. The activity of Irazú has been essentially the same for the past number of years.

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The Nicaraguan Volcano Masaya and Its Caldera

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Abstract—The Masaya Caldera and its included vents offer the volcanologist unusual opportunities for study. The caldera, which measures 11.2 by 6.0 km, is of the Hawaiian type and contains eleven recently active vents. The Masaya-Nindiri group of vents have been the most active in historic times and descriptive accounts of them go back to 1529. A sympathetic relationship between at least four or five volcanoes in the Nicaraguan chain is indicated by coincidence of eruptions. Cyclic activity in these volcanoes is strongly suggested by records of eruptions during the 19th and 20th centuries and may be substantiated by further data. The Masaya rocks are augite-olivine basalts of uniform composition. Attempts to control the emission of gases which have devastated a valuable coffee-producing region have proved futile but have provided new insights into the structure and behavior of the Volcano.

Introduction—Of all the volcanoes in the Central American chain, Masaya has consistently been the most active in historic times. Thanks to relatively complete records going back as far as the early 1500's and an abundance of active neighboring vents, the Volcano offers unusual opportunities for study.

Situated 25 km southeast of Managua and about the same distance west of Granada, it lies in the very center of the Nicaraguan population. In recent years, the persistent fume-clouds have caused losses estimated in hundreds of thousands of dollars to the coffee growers of the Department of Carazo, and interest in the Volcano has become more than academic. It is especially strange, therefore, that despite innumerable descriptive accounts, no true geological study of the Volcano has ever been made.

The Caldera—The Masaya Caldera is an elongated basin measuring approximately 11.2 by 6.0 km with its major axis trending NW–SE. It is bounded on all sides by precipitous cliffs ranging up to nearly 300 m in height. Recent lava flows which have flooded the Caldera and in one place have overflowed the northeastern rim make it impossible to measure the original depth. The eastern extremity of the Caldera, which contains Lake Masaya, has probably remained closest to the original level, and there it is possible to measure a difference of elevation between the top of the rim and the lake bottom amounting to approximately 200 m. The original floor of the Caldera must lie at an elevation of less than 50 m above sea level. The highest portion of the rim, on the western side, rises about 500 m above sea level.

The axis of the Caldera as a whole corresponds to the general tectonic strike of N45°W. Its relation to the Mateare – Las Nubes Fault Scarp is not clear, but it is certainly not reasonable to suggest, as others have done, that these escarpments are outer rims of some greater caldera. One gets the impression of 'nested calderas' when viewing the series of fault scarps from certain points, but a glance at any accurate map or aerial photograph quickly dispels this illusion. The only distinctly concentric fault is a badly eroded step to the south near the small town of La Concepción.

In profile, the Caldera resembles an enormous, shallow crater with steep sides and a relatively flat bottom. Beyond the walls, the rim slopes away gently on all sides, and it is easy to visualize a broad hill or mountain that once must have occupied the site of the present depression.

There can be little doubt that what we are dealing with here is not an explosion crater but a subsidence basin. Aside from the fact that no proven explosion crater has ever been found measuring more than a kilometer and a half in diameter the general form of the structure rules out such an origin.

First, and most apparent, is the insignificant size of the rim, the total volume of which falls far short of making up for the 13 km^3 of the depression, to say nothing of the volume of the overlying hill-mass which existed prior to formation of the Caldera. Moreover, there is remarkably little fragmental debris other than a few blocks of older lava scattered along the rim. The greatest part of the material exposed in the walls of the rim is normal, bedded ash and cinders laid down over a considerable time interval by various eruptions.

Secondly, the vertical walls of the Caldera could not have been formed by an explosive force. In all large explosion craters the form is essentially funnel shaped rather than cylindrical.

Finally, no radial faults of importance have been found on the outer slopes. In the case of explosive ruptures the pattern of faults is predominantly radial like cracks in a plate of safety glass shattered by a central blow. The faults around Masaya are

curved and concentric like those in the ice on a frozen pond in which the water level has receded.

Since the basin is not an explosion crater, we must seek another explanation of its origin. All other calderas in Nicaragua appear to have resulted from collapse following close upon Krakatoan eruptions. (To date, a total of eight major calderas have been recognized in Nicaragua, not including the Nejapa Pits and certain basins of doubtful origin. In order of size these are: (1) Masaya, 11.2 × 6.5 km; (2) unnamed caldera north of Lake Nicaragua, 7.9 × 6.5 km; (3) Apoyo, 7.2 × 7.0 km; (4) unnamed caldera on northwest side of Momotombo, 4.5 × 3.5 km; (5) Apoyeque, 2.8 × 3.0 km; (6) Jiloá, 2.5 × 2.7 km; (7) Cosegüina, 1.5 × 1.0 km; and (8) Asososca, 1.3 × 1.2 km. All but the recently recognized caldera north of Lake Nicaragua are part of the active chain. Only Cosegüina was formed within historic times, in 1835.) Masaya, however, possesses certain features which set it apart from the others. First, its shape is more irregular. Its scalloped outline contrasts very noticeably with the regular, circular outline of the Cosegüina type. The Masaya Caldera appears to have been formed, not by a single engulfment, but by numerous, coalescing collapses extending over a considerable time interval. This is shown both by the interlocking arcs that make up the marginal fault system and the various stages of erosion about the rim. Second, no trace of the characteristic pumice beds, which are so voluminous about the other calderas, can be seen in the immediate vicinity of Masaya. On the eastern face of the Las Nubes Fault Scarp nearly 600 m of bedded pyroclastic deposits are beautifully exposed, and although the great majority of this material clearly comes from Masaya, white pumice layers are conspicuously absent.

In order to find a close analogue to the Masaya Caldera we must look beyond Nicaragua to the classic volcanoes of Hawaii. The resemblance to these volcanoes, both in form and activity, is very striking. The large summit calderas of Mauna Loa and Kilauea, though considerably smaller, are bounded by similar arcuate faults and steep, irregular walls like those of Masaya. They are commonly believed to owe their origin to gravity subsidence of the upper crust following withdrawal of magma beneath. Collapse usually occurs independently at various points along a rift zone, and when a number of individual pits are joined the resulting depression is generally elongated in the direction of the rift zone. Various names have been applied to the Masaya basin, such as 'sink,' 'maar,' and 'collapse crater,' but it is a true caldera within the definition of *Williams* [1941], which simply states that calderas are "large volcanic depressions more or less circular or cirque-like in form, the diameters of which are many times greater than those of the included vent or vents" and does not make any distinction as to origin other than that they are subsidence forms. In order to differentiate this caldera from Cosegüina or Crater Lake type it should be sufficient simply to designate it a Hawaiian-type caldera.

In order to account for the undermining of the crust which brings on the collapse of calderas in this category many processes have been suggested.

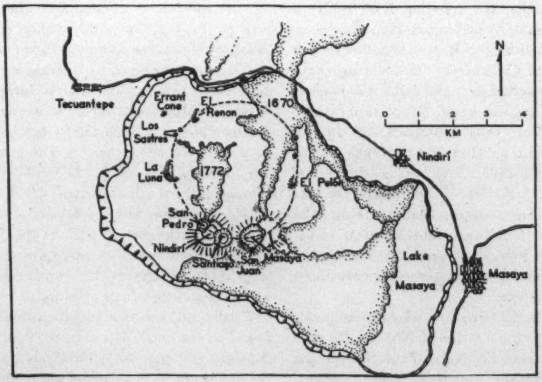

FIG. 1 – The Masaya Caldera

These include effusion of lava from lower levels and injection of dikes and sills. At Masaya there is no evidence of important lava flows having been erupted from vents or fissures outside the perimeter of the Caldera. Evidence of dike injection is likewise lacking. As will be shown below, however, the fluctuation of the magma level, even over a period of ten years, can be very great, and it appears that the collapse of the Caldera can be adequately explained by a recession of magma very similar to what has been observed, though of greater dimension. This, of course, implies a relationship between the superficial area of the Caldera and the horizontal extension of the magma chamber. Although it is difficult to conceive of a magma chamber measing nearly 50 km³ in cross section, migration of the active center would allow collapse into evacuated throats of more acceptable size.

Within the Caldera, the recently active vents are distributed in a nearly perfect, circular pattern. This ring probably outlines the boundary fault system of an earlier collapse crater, some 3.5 km in diameter, which has been buried by post-caldera lavas. No doubt other such craters have been formed on the caldera floor only to be filled again by lava and obliterated.

The vents—At least eleven vents can now be recognized within the Caldera, all of which lie in the northwestern extremity. All but one lie in a circular pattern, the single exception being a very small cinder cone (Errant Cone) lying about 500 m outside the ring toward the northwest (Fig. 1). The vents on the south side have been the most active of the group; all others have been cinder cones of short life.

Outside the rim are two small knobs on the north side near the lava flow of 1670 and another cone east of Lake Masaya which is crowned by an old army cuartel. None of these preserves its crater. They appear to be older than the Caldera. At a few points along the northern rim, notably near the Tecuantepe-Masaya road where it starts down to cross the lava beds, there are signs of brief explosive activity of a very minor nature.

The Masaya-Nindirí vents (Fig. 2) compose a large, complex structure rising more than 400 m above the caldera floor. Built by many successive layers of massive olivine basalt, this center of ac-

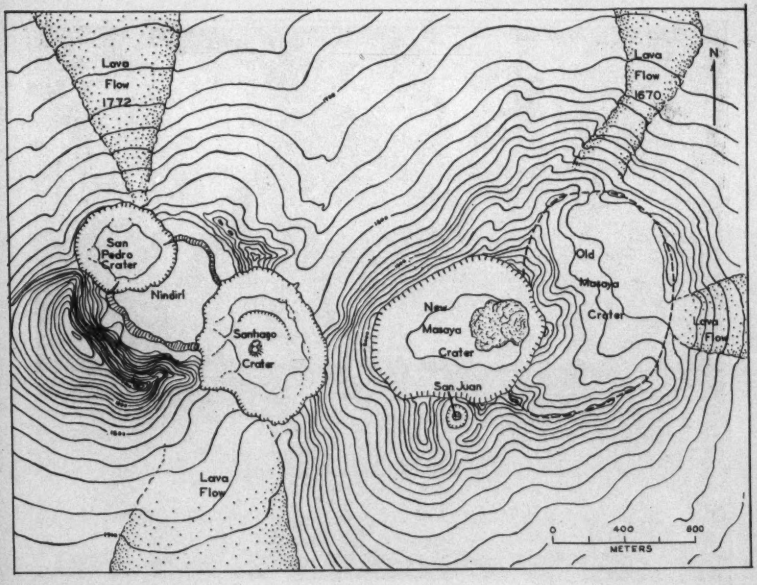

FIG. 2 – The Masaya-Nindirí vents

tivity has been the source of practically all the visible post-caldera lavas. These lavas, which have flooded a large portion of the caldera, are very recent, some having been effused during historic times, and all the surface flows can be traced to either the Nindirí or Masaya crater.

At first glance, especially on the ground, this interesting maze of craters appears hopelessly confused. Careful study of the structure, however, reveals the plan of their development. This system is best understood if one first recognizes the two original twin volcanoes, Masaya on the east and Nindirí on the west. Each of these is a truncated cone. They are approximately equal in size and elevation and apparently grew simultaneously, merging in the later stages until only a shallow saddle now separates them. The rocks of which they are constructed are olivine basalts laid down in massive flows up to ten meters in thickness with minor interbeds of scoria. Twenty-four of these flows are magnificently exposed in the east wall of Santiago Crater.

The principal vent of Masaya, now only partially visible, was located in the southeastern corner of the present crater. Before the appearance of the most recent crater, Masaya seems to have been a fairly steep sided cone, some 800 m in height, with a crater on its east side that was later filled with lava. The prevailing east winds probably built a higher rim of pyroclastic ejecta around the western side of the vent. A small parasitic cone, San Juan, lies on the southern flank. The large crater now visible is a summit sink measuring 700 by 600 m across and approximately 200 m in depth. It was formed in very recent times. Whether or not it is the same crater that existed at the time of the first visits of the Spanish explorers in 1529 is not certain.

The great flow of lava that covered much of the northern part of the caldera, overflowed the rim, and ran another nine kilometers northward is believed to have been erupted in 1670. Since this flow can be clearly traced to the Masaya vent it is presumably older than the present crater, for no lava could have come from this vent after the formation of the crater without completely filling it (as happened with the Nindirí crater in 1772). The level of the crater floor at the time of the 1670 eruption must have been very near the level of the rim of the present crater, for the northeastern

FIG. 3 – Aerial photograph of the Masaya Caldera

margins of the rim are splattered with globs of cow-dung lava that appear to have come from a lava lake near by. Furthermore, there is good reason to suspect that the pit seen by *Oviedo* [1855] in 1529 was actually the older, easternmost crater that has since been filled, the outline of which is clearly visible, especially in aerial photographs (Fig. 3). Oviedo's drawing (Fig. 4) strongly suggests that this is the case. Moreover, his narrative tells us that in going from the Nindirí crater he climbed a ridge of hills to the east and followed a trail in that direction until he arrived at the second crater, indicating that he must have passed directly over the summit of the hill that now contains a crater. He stated that the crater he saw was funnel or trumpet shaped. The present crater, on the contrary, is flat bottomed and cylindrical.

Oviedo's account reads:

Junto e continuando con aquella boca (Nindirí) alta deste cerro sube un cuchillo de sierras a la parte del Leste, sobre el camino por donde van a ver lo ques dicho; y alli esta otra hondura tan grande como la que tiene el poço, y esta mas alta aquella cumbre, e de noche humea, e de dia no se ve tan claro el humo della, mas de noche da la mesma claridad que la otra, e se mezcla el un resplandor con el otro; pero en lo baxo della no hay plaça, sino un hoyo que en la abertura arriba es grande e desciende, disminuyendose a forma de una tolba, y en lo baxo paresçe todo çeniça.

If such is the case, the crater seen by Oviedo was filled with lava between 1529 and 1670, and the present crater was formed sometime after the eruption of the latter date. After the collapse of the cone into the present crater, lavas were poured out on the floor on two or three occasions, but never in large quantities. The last effusion came from a distinctly visible vent which lies directly under the eastern wall in the vicinity of a lava core filling the earlier crater.

The second of the two great craters seen by Oviedo has changed even more radically than that of Masaya. In 1529, Nindirí crater was about 216 m deep and contained a lava lake. Since it was into this crater that descents were made in hope of extracting gold and silver from the molten lava, which was believed to be metal, descriptions of the crater and its state of activity are very complete. It was very steep sided, circular or slightly elliptical in plan, and had a flat bottom. The western rim was the highest, and at that time the lava flow which had emerged from the eastern rim of Nindirí and can now be seen on the southern slope of Santiago was very fresh. In 1529 the 'well' which contained the lava lake was situated near the southern side of the crater floor. It measured about

FIG. 4 – Oviedo's drawing of the Masaya-Nindirí vents, probably looking west from the town of Masaya

12 by 15 m in size, and the lava lay at a depth of some 66 meters below the mouth.

By the time of Fray Blas del Castillo in 1537 changes seem to have occurred. The vent was situated closer to the eastern wall, and the lava lay only a few meters below the floor level. Since Fray Blas described the crater as being more elongated than circular as Oviedo had seen it, *Sapper* [1925a] believed that an eruption must have taken place between 1529 and 1537. But there is no mention of such an eruption in all the numerous accounts of that period, and it seems more likely that the western wall had fallen in, for according to the account of Fray Blas there was much talus on this side.

From the descriptions of the observers who descended into the crater in quest of precious metals we can deduce that the character of the lava lake was very similar to what has been seen in recent years in the Halemaumau Crater of Kilauea. It was an incandescent, moving liquid with floating crusts of scoria. The lava level fluctuated between considerable extremes, and at times spatter was flung out upon the crater floor.

The lava lake had disappeared by 1570, but may have returned intermittently until 1772 when Nindirí completely filled its crater and overflowed

FIG. 5 – Santiago, Nindirí, and San Pedro Craters, looking west; jeep on rim of Santiago shows size

FIG. 6 – The northwest wall of Santiago Crater showing the lava filling of Nindirí

the northern rim. This filling is beautifully exposed in the west wall of Santiago and the east wall of San Pedro. It measures about 600 m in diameter and nearly 200 m in height. The central portion of the filling has subsided approximately eight meters producing two circular and concentric fault steps with diameters of 430 and 610 m (Fig. 5 and 6).

The Santiago and San Pedro Craters on the east and west sides of Nindirí respectively are simple collapse forms of almost ideal symmetry. Of the two, Santiago is the larger and by far the more active. It measures 500 m in diameter and 206 m in depth. The present level of the floor of Santiago is the same as the level of the Nindirí crater floor

FIG. 7 – Pahoehoe lava erupted on the floor of Santiago Crater in 1946

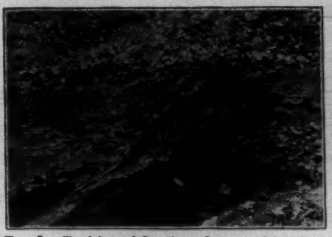

FIG. 8 – Faulting of Santiago floor resulting from subsidence of the center (left)

FIG. 9 – The presently active vent of Santiago

before the filling. As will be seen below, both Santiago and San Pedro were formed in the 1850's approximately 75 years after the lava eruption from Nindirí.

Subsequent to the first collapse two later subsidences have lowered the level of the Santiago floor. At the present time the floor, which is covered by pahoehoe lava of 1946 (Fig. 7), has been faulted around the north and northeast sides in an arcuate manner, and the inner block has a maximum displacement downward of six meters (Fig. 8).

The presently active vent in Santiago (Fig. 9) is located somewhat south of the center of the floor and consists of two orifices which are undoubtedly joined at a shallow depth. A steep rim of scoria about ten meters in height surrounds the vents on all but the northern side. Each of the vents has a diameter of approximately 50 m at the surface and narrows to about 30 m at a depth of 60 m.

Activity—Although the records of the activity of Masaya go back as far as the 1520's, there are many gaps, and during the first three hundred years reports were limited largely to the more violent and spectacular phases. It is only in the last one hundred years or so that records approach completeness, and even during this period there is

good reason to question whether they are exact. Reports that have come down to us are merely fortuitous records of infrequent travelers who passed through the region and had the interest to observe the volcano and write what they had seen. If the accounts were printed and survived the years of disinterest this again was mere chance. Any one who has attempted to compile a fairly complete and continuous record of the activity in any area where there have been no truly interested students of the volcanoes appreciates the problem of untangling hazy stories and contradictory reports, even for very recent events. We must accept the fact that until a systematic program of reliable observation is permanently established, our records will be pitifully inadequate for anything approaching a scientific study of these Central American volcanoes.

At the present time there is reason to believe that the activity of Masaya is not unrelated to that of other Nicaraguan volcanoes. Certainly the data available now are sufficient to suggest a general sympathetic cycle among at least four or five of the active volcanoes, and it is possible that more complete information would strengthen the case.

Little can be said concerning the period from 1529 to the middle of the last century. During the period 1529 to 1538, however, Oviedo, Fray Blas del Castillo and others [*Sapper*, 1925b] made close inspections of the Masaya-Nindirí group and left very detailed descriptions of the conditions at that time. Masaya (probably the now-flooded, easternmost crater) was in a state of solfataric activity and had shortly before given off flames from a lava lake or fountain. We know that a lava lake existed in Nindirí and persisted at least until shortly before 1570. In 1670, lava from the eastern Masaya vent covered a large area of the Caldera floor, spilled over the northeast rim and ran nine kilometers beyond. This appears to have been an exceptionally fluid flow, probably of high gas content.

There are no accounts of ash or cinders being erupted during the 17th or 18th centuries. In fact, for a full century, from 1670 to 1772 there is no record of activity whatever. The western Masaya crater was probably formed during this period, but this is not certain. The lava which poured out on the floor of the new Masaya crater and is now clearly visible was perhaps contemporaneous with the lava from Nindirí in 1772. It appears from the stratification and lack of columnar jointing in the lava that filled the Nindirí crater that this filling was interrupted, although it probably took place over a short time interval. When the crater was filled, the lava overflowed and ran down the northern slope about two kilometers. This flow was more viscous than that of 1670.

Out first reliable description of the Volcano in recent times is that of *Stephens* [1841], the U. S. Chargé d'Affaires in Central America. This remarkable man, the same who discovered the great Mayan ruins of Copan, passed through Masaya in 1840, climbed the Volcano, and left an excellent description of what he found. We are fortunate in having this account, for Stephens visited the Volcano only a few years before the formation of the Santiago and San Pedro craters. Apparently he found no signs of activity whatever. He mentioned the existence of two large craters, which must have been the Nindirí crater and the new Masaya crater. From his description it appears that the Nindirí crater had already subsided slightly since the 1772 eruption and that the eastern rim had fallen in.

About ten years later, *Squier* [1856] went through the town of Masaya and visited the lake. He did not climb the Volcano, which evidently still showed no signs of activity.

Our accounts of the events of the 1850's come to us second hand through the works of *Montessus de Ballore* [1888], a French scientist to whom we are indebted for much of our data on the activity of the Central American volcanoes. Shortly after the middle of the last century great changes began to take place in the Nindirí crater. The first indication that the volcano was still alive came on June 8, 1852, when Lake Masaya, together with Lakes Tiscapa, Asososca, Apoyo, and others, began to 'boil.' Most likely this 'boiling' was actually an emission of gases from the lake bottom. On June 29, underground rumblings were heard, and it is reported that in the following month a small amount of lava was effused from the western crater (Nindirí). As *Sapper* [1925a] points out, one can find no trace of this lava in the field, but possibly it did not overflow the crater rim, or if it did, flowed out on the east side, which Stephens stated was the lowest, and was covered and lost by the later collapse of Santiago. On April 9, 1853, clouds of steam and gas began to rise from the Volcano indicating that an open vent existed and that the magma level was low enough to permit emission of considerable quantities of gas without noticeable eruption of pyroclastic ejecta. How long this continued is not known.

Around the end of 1858 and the beginning of 1859 another series of events occurred. On November 10, 1858, there was a mild eruption, and on the following January 27, after a strong subterranean

rumbling, there was an ash eruption that reportedly burned the forest of Masatepe to the south. Most likely the 'burning' was the effect of gas clouds that killed the leaves of trees as they do today whenever a change of wind shifts the gases to an area of fresh vegetation. On March 27, another strong detonation was heard and was followed by eruption of more ash showers.

It was undoubtedly during these last two convulsions that the Santiago and San Pedro craters were formed. The ash erupted was probably a fine lithic dust eroded from the wall rocks of the fractured zone by the suddenly released gas and steam. The sequence of events conforms to a pattern that has been recognized in similar occurrences elsewhere in Nicaragua [*McBirney*, 1955ab]: a rise of magma (the lava effused in 1852) which fluxed the solid overlying rocks, recession (reflected by the change to solfataric activity in 1853), collapse, and the release of low temperature gases through the fracture (1858–59).

Following this, no close examination of the Volcano is known of until that of *von Seebach* [1892], who visited it in 1865, some seven years later. The description of what von Seebach found at that time fits the present situation: the Santiago and San Pedro craters had been formed. He reported no activity except weak fumaroles. *Sapper* [1913, 1925a] made his first visit to the Volcano in 1897 and saw nothing but weak fumaroles on El Pelon and "in the interior and to the northeast of the western crater."

There is no record of renewed activity until shortly after the turn of the century when another series of eruptions took place. These were preceded by tremors and underground rumblings on June 25 and July 6, 1902. By July 15, Santiago was smoking. Eruptions of fresh cinders occurred, and when the Volcano was visited in June 1904 there was a small cone around the vent in the bottom of Santiago. The activity gradually declined, but during the last days of 1905 and the first days of 1906 strong shocks were felt in the city of Masaya and cracks were reported to be giving off smoke and ash between Santiago and El Pelon. These cracks have not been observed in the field.

In 1919, a new period of activity opened in Santiago with frequent gas and cinder eruptions. We do not know in what manner the vent was opened, but Sapper visited the Volcano in 1924 and reported that the vent of 1904 was not to be seen and that a new vent on the north side was in very strong solfataric activity. He also stated that the crater was much enlarged but did not say in what way. After 1924 there does not seem to have been any eruption of cinders, but gas emissions continued with the same intensity until February 1927 when they were brought to an abrupt end by subsidence of the crater floor.

In 1946 the vent was reopened. Again it has been impossible to get exact details as to how this occurred, but several persons state that there was incandescent lava in the bottom of Santiago during that year. This seems likely, for the lavas now found on the floor appear very fresh, have no mantle of cinders from the 1919–1927 activity, and completely cover the 1924 vent reported to have been on the north side of the floor. Moreover, the faulting and general configuration of the floor as seen today does not coincide with the maps and diagrams of *Schönberg* [1927]. We are led to conclude that the present vent was opened by a rise of magma contemporaneous with that of the Cerro Negro eruption of the same year. As the magma receded, the vent began to emit gases at an increasing rate. The fume clouds decreased only during the later part of 1950 and the beginning of 1951, during which time Cerro Negro again erupted lava, and it appears that the decrease is attributable to a simultaneous rise of lava in the Santiago vent. Although it might appear that gas emission should increase with a rising magma, the reverse seems to be true. (G. A. Macdonald of the Hawaiian Volcano Observatory states in a personal letter to the writer (February 17, 1955): "Regarding your comments on the increase of fume at Masaya, when the level of the lava column drops, that is exactly the condition that was found here at Kilauea through the period of the active lava lake. Jaggar commented repeatedly on the fact that the Halemaumau pit was essentially clear and free of fume when the lava level was rising, but that the pit became fume-filled and visibility very poor at times of falling lava level. There seems to be a similar tendency, though less marked, at Mauna Loa. I believe the same phenomena have been observed at Asama and possibly elsewhere in Japan.") Since 1950 the volume of gases has become very great, although precise measurements have been impossible.

Relation of Masaya activity to other volcanoes—If all the records prior to the 19th century are rejected as inadequate and only those from 1840 to the present are considered, four periods of activity can be distinguished at Masaya: 1852–59, 1902–05, 1919–27, and 1946 to the present. It is fruitless to lament the incompleteness of our data for the other volcanoes during this time. From what is known, it can be seen that each of these periods is repeated elsewhere in the Nicaraguan chain by activity in

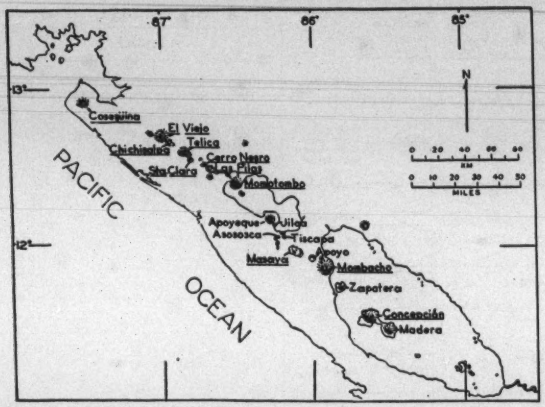

FIG. 10 – The principal Nicaraguan volcanoes; names underlined are volcanoes that have been active within historic times

at least one other volcano and in most cases two or three. The principal volcanoes of the chain in Nicaragua are shown in Figure 10.

One is tempted to deduce a recurrent cycle in the volcanoes during this time. If the great Cosegüina eruption of 1835 is interpreted as the result of a preceding magmatic fluctuation, the following periods are divided roughly into five 17-year cycles punctuated by the following primary eruptions:

1835	Cosegüina
1850–52	Cerro Negro, Momotombo, Mombacho (?), and Nindirí
1867	Cerro Negro
1883–85	Concepción and Momotombo
1902–05	Concepción, Momotombo, and Santiago
1919–23	Concepción, Cerro Negro, and Santiago

After the 1919–23 eruptions, the regular spacing is broken, for it is not until 1946 that primary activity returned. In the intervals between these eruptive periods, there are no recorded eruptions that were not solfataric except, perhaps, that of Cerro Negro in 1914, which is of a very doubtful nature, since there are few reliable data. Although mud flows were reported, there is no record of fresh lava or cinders having been erupted. All the eruptions in Nicaragua which produced fresh cinders or lava occurred during the periods listed above, which were of an average duration of about 27 months.

This apparent cycle is represented diagramatically in Figure 11. The vertical lines dividing primary activity (eruptions of lava or juvenile cinders) from secondary activity (solfataric or fumarolic activity) is intended only to distinguish between two types of volcanic phenomena and in no sense reflects positive or negative values.

Although proof of such a cycle is not conclusive, I have felt that it should be pointed out here, for its existence, which has never before been suspected, may be verified or refuted if future observations are directed toward that end. In detail the record shows the following:

The 1852–59 activity at Masaya, which culminated in the collapse of the Santiago and San Pedro craters, follows close upon the birth of Cerro Negro in 1850 and cinder eruptions from Momotombo in 1849 and 1852. *Crawford* [1902] reported the eruption of a small cinder cone, 'Pilas' (not to be confused with the Las Pilas near Leon), on the north flank of Mombacho in 1850. No other record of this eruption has been found, and it is considered doubtful. During April–May, 1850 a large quantity of basic, juvenile material, both pyroclastics and lava, was erupted from Cerro Negro. At Masaya, as we have seen, the crater of Nindirí was reported to have effused lava during July of 1852. After an interval of about six years the two craters collapsed, suggesting that the rise of magma had fluxed and weakened the older rocks until, with recession of the magma, the crust collapsed.

Again, the period of activity at Masaya during 1902–05 was accompanied by an eruption of cin-

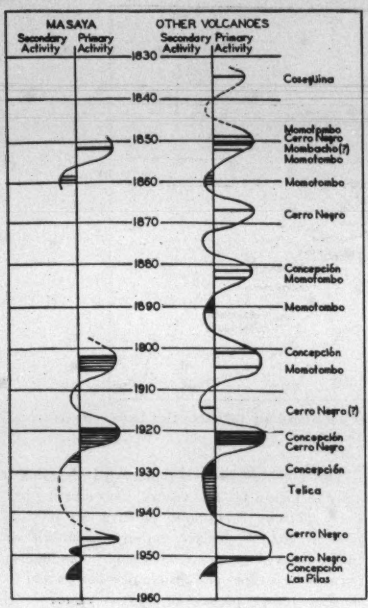

FIG. 11 – The relation of Masaya activity to other Nicaraguan volcanoes

ders from Concepción in 1902, about the same time that cinders were being erupted from Santiago. Momotombo responded in 1905 with a major cinder and lava eruption, and then activity throughout the country all but ceased.

With the exception of the already noted doubtful eruption of Cerro Negro in 1914 all was quiet until 1919 when the third period started with gas and cinder eruptions from Santiago. Concepción started in 1921 to erupt cinders, and Cerro Negro joined in with cinders and considerable lava in 1923. Cinders were not erupted from Santiago or Concepción after 1923 or early 1924, but as long as the Santiago vent remained open gases were emitted. No further eruptions took place until the fourth and latest period started in 1946.

The reopening of the Santiago vent in 1946, as described above, seems to have resulted from a new rise of magma, which caused the floor of the crater to be flooded with lava. A few months later Cerro Negro erupted cinders and lava. During the next three years the gases of Santiago increased

TABLE 1 – *Chemical analysis of 1670 lava**

Compound	Per Cent
SiO_2	50.60
Al_2O_3	17.29
Fe_2O_3	8.08
FeO	3.54
MnO	0.17
MgO	5.78
CaO	11.90
Na_2O	1.99
K_2O	1.19
TiO_2	0.44
P_2O_5	tr
H_2O^+	0.005
H_2O^-	0.01
Total	100.995%

* Analysis by Martin and Carlisle, Albuquerque, New Mexico.

and then fell off again when Cerro Negro erupted a second time in November–December, 1950. Following this, the gases of Santiago steadily increased again, gas eruptions started in Concepción, and on October 23, 1952 Las Pilas opened its kilometer-long fissure and blew off low temperature gases and lithic debris from the wall rocks [*McBirney*, 1955b]. At the present time Santiago continues to emit fumes at what appears to be its maximum sustained rate, and Las Pilas has developed a steadier emission of gases, almost equal in volume to that of Santiago.

Petrography—The rocks of Masaya are remarkably uniform in character, and regardless of the source or age, no apparent distinction in composition can be detected. They are, almost without exception, olivine-augite basalts. A specimen of the 1670 lava was selected for the analysis shown in Table 1.

The following specimens were examined in thin sections and are illustrated in Figure 12.

(A) MAS-1, diam. 2 mm. Lava flow near the base of the caldera wall above Lake Masaya. Coarse-grained, intersertal olivine basalt consisting of large clusters of plagioclase, very abundant olivine, and some augite in magnetite dust loaded glass.

(B) MAS-2, diam. 2 mm. Large blocks in a thick agglomerate bed above Lake Masaya. Basalt with rare phenocrysts of plagioclase in an intergranular, porous groundmass consisting of plagioclase, magnetite, augite, and olivine.

(C) MAS-3, diam. 2 mm. Lava flow of 1670 from Masaya crater. Dense, non-porphyritic, hyalopilitic, augite basalt.

FIG. 12 – Masaya rocks

(D) MAS-4, diam. 2 mm. Lava flow of 1772 from Nindirí crater. Olivine-augite basalt with interlocking phenocrysts of plagioclase, olivine, and augite in a very dense, intergranular, porous groundmass consisting of plagioclase and olivine.

(E) MAS-5, diam. 2 mm. Lava filling of Nindirí crater. Coarsely porphyritic olivine-augite basalt with an intergranular groundmass of cristobalite, tridymite, calcite, and crystallized magnetite.

(F) MAS-6, diam. 2 mm. Wall rocks in the

north side of Santiago crater. Intergranular olivine-augite basalt with abundant magnetite and hematite.

(G) MAS-7, diam. 2 mm. Small dikes in the north wall of Santiago crater. Non-porphyritic, hyalopilitic, augite basalt with abundant vesicles lined with yellowish-green nontronite (?) or chlorophaeite.

(H) MAS-8, diam. 2 mm. 1946 lava on the floor of Santiago crater. Vitrophyric augite-olivine basalt.

(I) MAS-9, diam. 2 mm. Ejecta from the presently active vent of Santiago crater. Augite basalt containing large phenocrysts of bytownite in a groundmass of black glass stippled with augite, etc., and reddened by fumarolic hematite.

(J) MAS-10, diam. 3 mm. Fragments in an agglomerate bed in the upper part of the Las Nubes fault scarp. Granodiorite with biotite, green hornblende, orthoclase, sodic plagioclase, quartz, and some chlorite.

Control of the gases—The large volume of sulfurous gases emanating from the Santiago crater and carried westward by the prevailing trade-winds to devastate the vegetation of a potentially rich coffee zone have often provoked speculation as to the possibility of controlling the fumes and even turning them to commercial use.

Following the extensive crop damage that started with the emission of fumes after 1924, the coffee growers of the Carazo region united to raise funds to bring two German engineers to Nicaragua to attempt to stop or reduce the gas emissions. The two men, Schönberg and Scharfenberg, proposed to do this by capping the vent and piping the gases up to the crater rim where they would be utilized in the manufacture of sulfuric acid. In this way it was hoped the fumes could be diverted from their damaging effect to a useful purpose.

The accounts of this work [*Schönberg*, 1927, 1934] make fascinating reading. At the end of a year and a half of intrepid struggle they had succeeded in suspending a metal pipe or conduit, one meter in diameter and nearly 800 m long, from the crater rim down to the vent. Then attempting to restrict the orifice and force the gases into the pipe they placed dynamite charges totalling about 500 kg about the walls of the crater. It was hoped that the rock blasted loose would fall down around the vent and effectively seal the entrance of the pipe. The charges were detonated on February 27, 1927.

The result, according to Schönberg, was a terrifying series of convulsions, explosions, and dust clouds ending in complete collapse of the crater floor. Doubts have been expressed as to whether the cataclysm was in fact brought on by the dynamiting or rather by a natural earthquake, eruption of the Volcano, or a combination of both. There is little doubt that the floor subsided and that the vent was closed; and that such a collapse could have been set off by a moderately strong shock is not unlikely.

The emission of fumes was completely stopped for a period of 19 years. In 1946 a new vent was opened, however, and soon was giving off gases in a manner identical with that during the period 1924–27. An area of some 30 km² across the Jinotepe Plateau has been rendered barren of all but a few scrubby weeds. This region stands at some 800 to 1000 m elevation and has all the properties of an excellent coffee zone. Many plantations established prior to 1924 and during the years of inactivity between 1927 and 1946 have had to be abandoned with considerable loss to individuals and to the national dollar revenue as well. Not only vegetation but wire fences, machinery, and all types of metal installations are attacked and quickly deteriorate. Even the cement factory at San Rafael del Sur, about 30 km from Santiago, is faced with a constant maintenance problem due to excessive corrosion of its equipment.

In 1950 the coffee growers again decided that something should be done about Santiago, and at their request the U. S. government sent R. E. Wilcox, a volcanologist of the U. S. Geological Survey, to Nicaragua. After studying the problem carefully and listening to all the locally advocated remedies, such as building a chimney over 300 m high to carry the fumes over the sierras, or dropping an atomic bomb into the crater, he wrote an excellent appraisal of the problem [*Wilcox*, 1951] and gave his recommendations for alleviating the situation. Wilcox very wisely declined the role of a Don Quixote and refrained from attacking the Santiago windmill with a grandiose solution.

Two years later, in August, 1952, D. N. Spencer, a U. S. citizen residing in Nicaragua, decided that the prevailing high price of sulfur justified a reconsideration of the possibility of utilizing the Santiago gases commercially. He turned the investigations over to the writer, who devoted 2½ months to the work.

In order to make an intelligent appraisal of the situation at that time it was necessary to study the bottom of the crater and the vent, which had not been examined first hand since Schönberg's last descent in 1927. The south wall was selected as presenting the fewest obstacles, and after considerable difficulty, rope ladders were lowered in sections and secured to steel anchor irons that

had been cemented into holes drilled into the solid rock. The 200 m vertical climb was rewarded with an excellent opportunity to study the vent at close range.

Across the principal (southern) vent a steel cable was stretched between two vertical stanchions, and on this a trolley system was mounted with a second cable that could be lowered vertically to sound the depth of the pit. Unfortunately it was not anticipated that the depth would be very great, and the cable used for the sounding, having a total length of only 115 meters, never reached lava. It was, however, proved that the magma level lay at a considerable depth.

By some unknown occurrence, perhaps caving in the deep interior of the vent, gases ceased flowing through the southern vent for two days on September 23–24, 1952 and were forced out the northern vent. This afforded a rare opportunity to see into the principal vent, and the extreme depth was verified, although it was impossible to make out details of the seemingly bottomless pit.

Temperatures were taken by means of a maximum mercury thermometer in the center of the gas stream approximately 15 m below the level of the rim and were found to be widely variable but not exceptionally high (between 250° and 300° C).

Gas samples were collected at a later period during 1954 by aspirating the hot gases through a sampling bulb and then allowing the bulb and gases to cool and condense while the collecting tube remained in the gas stream. To date it has been impossible to obtain satisfactory samples, and those taken have been highly diluted with atmospheric gases. Water vapor, CO_2 and SO_2 were found to constitute a small proportion of the volume.

When examination of the crater floor revealed numerous concentric faults in the 1946 lavas it was surmised that further subsidence was possible, if not imminent, and investment in the project would be hazardous. Although Santiago might continue to emit gases for many years to come, there is little to prevent it from stopping abruptly at any time.

This fact suggested that an artificial collapse might easily be initiated, and it was decided that an attempt should be made at closing the vent. After securing approval of the President of the Republic and the Minister of Public Works, work was started on a device for exploding a strong charge as deeply as possible in the throat of the vent and thereby loosening the crater floor. Unfortunately, a near fatal accident during the course of the ensuing work left the writer with a broken arm and little inclination for continuing. Later, in August, 1953, the Nicaraguan Air Force dropped two medium size aerial bombs into the crater without effect.

Future relief from the gas emissions may come through a new rise of magma into the throat of the vent or a natural collapse of the crater floor. Fortunately, little is to be feared from lava eruptions because of the large volume that must be filled before any of the existing craters overflow. Even an eruption of lava from the flanks of the Nindirí-Masaya group or from any of the other vents on the caldera floor would not be likely to endanger any center of population.

Future observations—Although patterns are suggested by the available data, no reliable means has been found to predict the course of future activity. The best that can be expected at this time is a gradual increase of knowledge accrued from many years of future study and the collection of factual data covering a longer period of time. Pursuing this course, we can trust that a greater understanding of volcanology will, as in many other sciences, bring eventual reward in the form of material benefits to man. In order to accomplish this, a program must be established to keep constant records of the activity within Nicaragua, and if possible, in the neighboring Central American republics as well. The cost of such a program would be slight in relation to the value of the information that would be gained.

Acknowledgments—It is gratifying to have an opportunity to express my deep indebtedness to Howel Williams of the University of California, not only for critically reading and discussing this work and assisting in the petrographic determinations, but also for his kind and patient counsel over a period of years that has been both a guidance and inspiration. Helmut Meyer-Abich of the Servicio Geologico of El Salvador also deserves my thanks for his assistance in the preparation of numerous thin sections and the collection of references. To Constantino Lacayo-Fiallos, Nicaraguan Minister of Public Works, I am grateful for the labor and funds he made available to enable me to construct an access road across the Caldera and up to the Santiago crater. Finally, D. N. Spencer, through his support and interest in problems of volcanology made it possible to undertake this and other studies of the Nicaraguan volcanoes.

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Observations of Underwater Volcanic Acoustics at Bárcena Volcano, San Benedicto Island, Mexico, and in Shelikof Strait, Alaska*

James M. Snodgrass and Adrian F. Richards

Abstract—Magnetic tape recorders and sonobuoy equipment have made possible a practical approach to the study of underwater volcanic acoustics. Underwater audio energy originating from Bárcena Volcano on San Benedicto Island, Mexico, was studied from plane and ship between November, 1952, and May, 1955, and tape recorded on four different occasions. The recorded sounds are of two kinds: a rumble with a pitch of approximately 125 cycles, and a higher frequency hiss. These sounds, unlike any of known biological or other origin, are discussed and a frequency analysis of the rumble is given. In order to determine the source of audio energy produced from Bárenca a triangulation method was devised by making an effectively simultaneous time and frequency analysis of selected portions of the acoustic spectrum from pairs of strategically placed sonobuoys. This technique was successfully used from shipboard in November, 1953. An unsuccessful attempt was made in August, 1953, to determine if audio energy generated from the active volcano Mt. Trident, in the Katmai National Monument, could be received in Shelikof Strait. The attempt is described to illustrate the technique used.

Introduction—The study of volcanic acoustics is in its infancy. The first recordings of volcanic sounds were made by *Perret* [1926, pp. 138–139] very early in this century who used a surface microphone, electromagnetic receiver, sapphire stylus, and a wax phonograph cylinder as his basic equipment to record underground rumblings in the Pozzuoli Solfatara near Naples.

More recently detonations of the 1950 Strombolian type of eruption of Oo-sima (O Shima), 68 miles south-southwest of Tokyo, were tape recorded by members of the NHK Broadcasting Bureau (Minakami, personal communication).

In 1952–53, *Dietz* and *Sheehy* [1954] ably demonstrated that low frequency volcanic sounds can travel great distances in the sea by correlating SOFAR records made in California with the trans-Pacific volcanic explosions of Myojin Reef located about 200 nautical miles south of Tokyo. However, these sounds, with a frequency of less than 500 cycles, were recorded as visual power levels on a drum recorder and are not audibly reproducible.

In recent years the availability of newly developed equipment has made possible a practical approach to the study of audio energy radiated from volcanoes. This paper reports on studies of underwater volcanic acoustics between November, 1952, and May, 1955, in two areas. Magnetic tape recordings were made at Bárcena Volcano on San Benedicto Island off the west coast of Mexico. A three-station listening survey across Shelikof Strait, between Kodiak Island and the Alaskan peninsula, was made in 1953 in an unsuccessful attempt to record sounds from active Mt. Trident volcano in the Valley of Ten Thousand Smokes.

Description of Bárcena Volcano—Bárcena Volcano, previously known as Boquerón or 'Big Mouth,' was born on August 1, 1952. The Volcano is situated on the southern end of three-mile-long San Benedicto Island which is located approximately 900 nautical miles south-southeast of San Diego, California, 218 miles south of the southern tip of Baja California and about 300 miles off the west coast of the Mexican mainland (Fig. 1). The birth of Bárcena and its development in 1952–53 has been summarized by *Richards* and *Dietz* [in press]. Briefly, a 1250-ft ash and cinder cone was erected within 12 days of the birth of the Volcano. Block lava half filled the crater in middle November, 1952, and in early December viscous lava pierced the eastern base of the cone and flowed out into the sea for over two months forming a delta of lava (Fig. 2 and 3). Bárcena became inactive in March, 1953. A strong emission of fumarolic steam continued to escape from the crater into 1954. Since August, 1954, only weak fumarolic activity has been observed from the crater and lava delta vent; the volcano is presumed to be dead.

Attempted SOFAR correlation—*Dietz* and *Sheehy* [1954, pp. 955–956] examined the SOFAR records at the Kaneohe, Oahu, and other stations in an attempt to correlate unknown sounds with known activity at Bárcena Volcano. They could not correlate any of the sounds received and concluded

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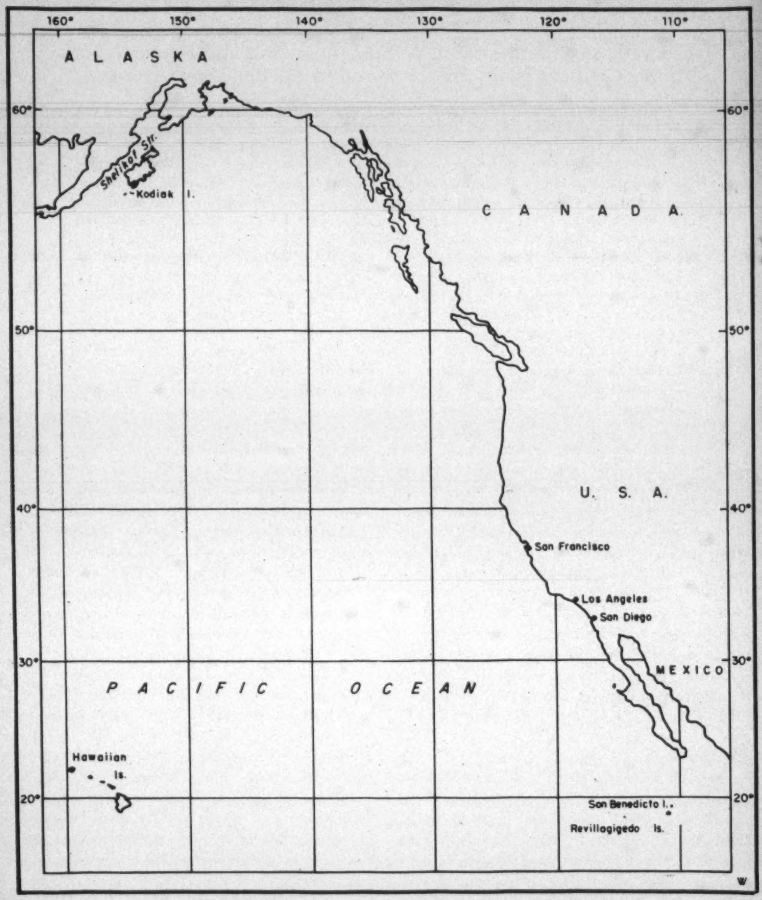


FIG. 1 – Location of San Benedicto Island, Mexico, and Shelikof Strait, Alaska

that either Bárcena was not producing sufficient energy into the water or that unknown submarine structures between the Volcano and Kaneohe prevented sound transmission.

Instrumentation—A brief summary of the instrumentation used at Bárcena Volcano is included in Table 1. The equipment used on all of the 1952–53 Navy flights consisted of Navy type AN/SSQ-2 sonobuoys, essentially small floating radio stations which contain a listening hydrophone sensitive to audio frequencies, a Navy R-316/ARR-26 sonobuoy receiver and a Magnecord model PT6-AH magnetic tape recorder and PT63-J amplifier. The tape recorder was mounted on a rubberized hair mattress to isolate it from the vibrations of the plane. Its power requirement was supplied by a 115-volt, 60-cycle dynamotor which operated from the 28-volt dc supply of the plane.

On the December, 1952, visit to Bárcena by the yacht *Observer* a stock model Zenith 75 hearing-aid

FIG. 2 – Proto-lava delta and Bárcena Volcano from the yacht *Observer*, December 10, 1952 (L. W. Walker photograph)

was slightly modified by substituting a sonobuoy hydrophone for the microphone. The hydrophone was connected to the hearing-aid through an impedance matching transformer and 100 ft of cable. This is the lightest, most portable equipment that has been used by the writers.

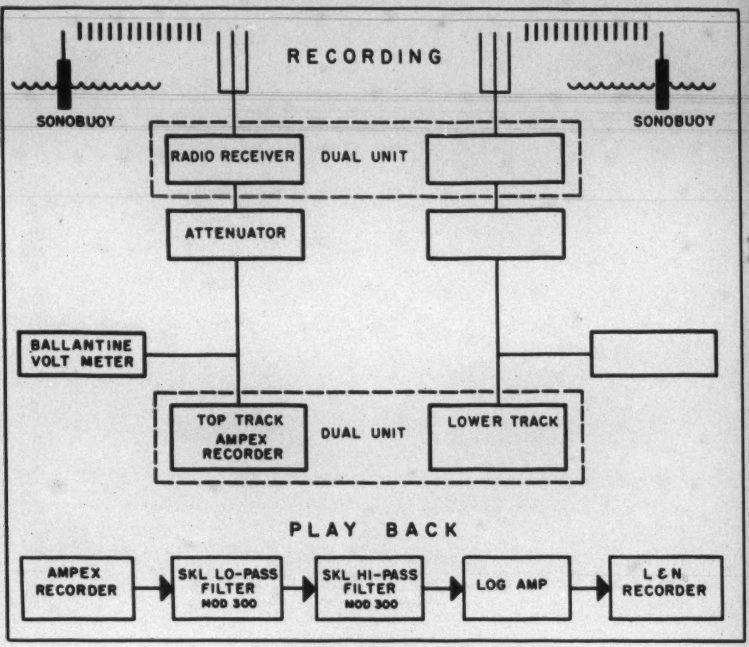
In March, 1953, the hydrophone-hearing-aid combination was again used at Bárcena Volcano from the Scripps Institution's research vessel *Crest*. The output from the hearing-aid at this time was fed directly into a model RP-402-A Concertone tape recorder.

Instrumentation of the triangulation technique used on the November, 1953, visit by the *R/V Crest* will be described in a separate section. A barium titanate hydrophone was also used during this visit. It was connected to a voltage amplifier and an Ampex model 403-2 tape recorder by approximately 110 ft of cable.

In May, 1955, a Navy Electronics Laboratory rochelle-salt crystal hydrophone was used with a voltage amplifier and a model RP-402-A Concertone tape recorder from on board the *R/V Crest*. The current to run the amplifier was supplied by a storage battery. The tape recorder was powered by a small gasoline generator isolated from the deck of the *Crest* by a partially inflated tire inner-tube.

The equipment used on the Shelikof Strait survey consisted of a sonobuoy hydrophone, 110 ft of cable, an impedance matching transformer, and a Stancil-Hoffman model M5A tape recorder, internally powered by batteries.

During the listening periods on the December, 1952, March, 1953, and May, 1955, expeditions to Bárcena Volcano and on the Shelikof Strait survey, all shipboard power equipment, including gyrocompass, was turned off to make the ship acoustically quiet. Experience gained on the 1953 Scripps Institution of Oceanography Trans-Pacific Expedition—when in the Bering Sea unsuccessfully listening for underwater volcanic sounds from volcanoes on the Aleutian Islands—and elsewhere has demonstrated that a ship must have all power equipment silenced for acoustic work of this type. Our studies have also demonstrated that a storage battery powered dynamotor is the most satisfactory means of supplying ac current to a high



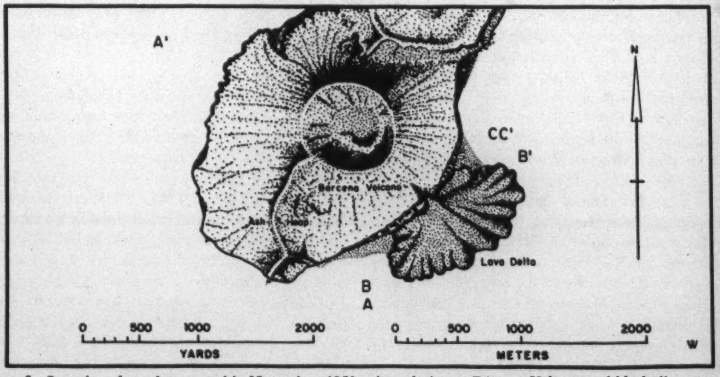


FIG. 3 – Location of sonobuoys used in November, 1952, triangulation at Bárcena Volcano and block diagram of acoustic triangulation instrumentation

fidelity tape recorder. Special gasoline generators are often difficult to isolate acoustically from the deck of a ship, or even if isolated, may induce spurious noise into the water through the air.

Underwater acoustic observations at Bárcena Volcano—Between November, 1952, and May, 1955, observations of underwater volcanic acoustics were made at Bárcena Volcano. These obser-

TABLE 1 – *Summary of underwater acoustic observations at Bárcena Volcano*

Date	Instrumentation	Observation Craft	Tape recorded	Sounds	Location of hydrophone or sonobuoy	Correlation and comments
Nov. 15, 1952	Sonobuoy, receiver, tape recorder	Navy PBM	Yes	Random rumble with a pitch of approx. 125 cycles	About one mile south of Bárcena volcano	No correlation with volcanic activity
Dec. 9–11, 1952	Hydrophone, modified hearing-aid	Yacht *Observer*	No	Continuous hissing	600 yd northeast of proto-lava delta	Noise of sea quenching incandescent block lava
Mar. 9–13, 1953	Hydrophone, hearing-aid, tape recorder	R/V *Paolina T*	Yes	Fish noises	500 yd southwest of lava delta	Equipment insensitive to low frequency sounds
April 16, 1953	Sonobuoy, receiver, tape recorder	Navy P4Y	No	None	About one mile south of lava delta	Power failure to tape recorder; no sounds heard when sonobuoy transmission monitored by ear
May 20, 1953	Sonobuoy, receiver, tape recorder	Navy P4Y	No	None	About one mile south of lava delta	Sonobuoys failed to work
July 13, 1953	Sonobuoy, receiver, tape recorder	Navy P4Y	Yes	Short bursts of hissing noise	About one mile south of lava delta	Sea quenching hot lava
Sep. 21, 1953	Sonobuoy, receiver, tape recorder	Navy P4Y	Yes	Rumble similar to that heard in Nov., seven-second bursts of hissing	About ½ mile south of lava delta	Rumble not correlated; hiss probably originated from sea quenching hot lava
Nov. 17–19, 1953	Sonobuoy, special recording equip., see Fig. 3	R/V *Crest*	Yes	Hissing	See Fig. 3	Triangulation for source of sounds; hiss probably due to sea quenching hot lava.
Mar. 25, 1955	Sonobuoy, special recording equip., see Fig. 3	Navy P5M	Yes	Fish noises	Same as illustrated in Fig. 3	Triangulation attempt from the air; Volcano inactive
May 1, 1955	Hydrophone, amplifier, tape recorder	R/V *Crest*	Yes	None	About ½ mile south of lava delta	Background noise produced by noisy generator too high to hear anything else; Volcano believed dead

vations are summarized in Table 1. For comparative purposes Table 2 lists the five reported observations of airborne volcanic sounds from 21 visits to the Volcano between the time of its birth on August 1, 1952, and the cessation of activity in early 1954.

The procedure on the 1952–53 flights was to drop two or three sonobuoys into the sea near the lava delta of the Volcano from altitudes of 500 to 10,000 ft. More than one sonobuoy was dropped on each flight to insure at least ten minutes of transmission time, for many of the buoys were defective, perhaps because they all had been used previously.

In December, 1952, the yacht *Observer* was anchored in 120 ft of water 600 yds from the seaward margin of the lava flow. The hydrophone was lowered to a depth of 90 ft. The only sound heard was the violent boiling noise of the sea quenching incandescent lava (Fig. 2). The level of this noise was sufficiently strong to mask completely all other underwater sounds, including normal wave and surf background noise.

In November, 1953, in conjunction with the triangulation technique a hydrophone was lowered to a depth of about 100 ft when the *R/V Crest* was near Bárcena. However, there was great difficulty in silencing the ship and essentially negative results were obtained. A similar difficulty was encountered in May, 1955.

During the time that the Volcano was visibly active, 1952–53, our equipment failed to receive volcanic sounds only twice. On the first occasion, in March, 1953, it is possible that low frequency sounds were present but below the 130 cycle lower limit of the hearing-aid. In April, 1953, no sounds attributable to volcanic activity were heard when the sonobuoy transmission was monitored by earphone. However, in November, 1952, and September, 1953, no low frequency sounds were heard when monitoring the transmission; yet these sounds were successfully tape recorded. Consequently, we feel that the absence of audible sounds, when monitoring the April transmission, does not necessarily indicate that low frequency sounds were not being generated by the Volcano.

Triangulation for source of sounds—A new triangulation technique to determine the source of

TABLE 2 – *Airborne acoustic observations at Bárcena Volcano*

Date	Sounds heard	Location of observer and comments	Activity of Bárcena at time of observation	Observer
Aug. 12, 1952	Continuous roar	Piper Cub of M/V *Intrepid* flying near Volcano	Continuous vulcanian-Peléan type eruptions	Chester Blasko
Nov. 13, 1952	Intermittent low rumble	M/V *Constitution* 8–10 miles east of volcano	Weak ash and steam eruptions, extrusion of lava into crater	Manuel Neeves, Jr.
Dec. 9, 1952	Intermittent low rumble	M/V *Star of the Sea* or *Challenger* abeam of vent of new lava breakthrough at a probable distance of 1–2 miles; observation questionable	Weak ash and steam eruption from crater, beginning of lava extrusion from basal vent	Name not known
Dec. 9–11, 1952	Loud hissing	Yacht *Observer* 600 yd off the new lava delta. Also similar hissing-grinding sounds heard from beach next to moving flow	Weak ash and steam eruption from crater, extrusion of lava into sea (see Fig. 2)	Lewis Walker and Adrian Richards
Jan. 12, 1953	Intermittent faint rumble	M/V *Cape Beverly* abeam of lava delta at a distance of ¼ mile	Very weak ash and steam eruption from crater, extrusion of lava from basal vent	Paul Lynn

the underwater volcanic sounds was devised and successfully used by the senior author from the *R/V Crest* in November, 1953. Navy AN/SSQ-2 sonobuoys were placed as shown in Figure 3. Two buoys were first placed on either side of Bárcena Volcano (A-A′), next on opposite sides of the lava delta but on the same side of the volcano (B-B′), and last off the northern end of the delta (C-C′). With this arrangement it was possible to receive both buoys simultaneously and yet remain at such distances that the miscellaneous ship noises were not picked up by the sonobuoys. Each buoy operated on different radio frequencies and the transmissions were received on a Navy R-316/ARR-26 sonobuoy receiver which served as a dual simultaneous receiving system. The receiver output was fed directly into an Ampex dual-track tape recorder, model 403-2. By this method it was possible to obtain a synchronized acoustic record from each sonobuoy with a maximum time error between the sound tracks of 50 microseconds. The block diagram of Figure 3 shows the relationship of the equipment used.

The recorded sound tracts were roughly analyzed for correlations of signals by playing them back and filtering in order to separate various portions of the acoustic spectrum. The output of the filters was fed through a logarithmic amplifier which drove a Leeds and Northrup Speedomax recorder. By replaying the tape, and recording over the same portion of the Speedomax chart, it was possible to obtain an effectively simultaneous time and frequency analysis from two buoys with respect to selected portions of the acoustic spectrum. An analysis of this type showed no correlation when the sonobuoys were placed on opposite sides of the volcano. Little correlation existed between buoys on the same side of the volcano, but on opposite sides of the lava delta. There was a high degree of correlation between buoys on the same side of the delta. At present this leads us to conclude that there was no activity within the Volcano which radiated energy within the acoustic spectrum, at least during the times when it was possible to record. Hissing sounds were heard from each buoy except the one located at A′. The localized contact of sea water with hot lava in the delta appears to be the most likely explanation of these sounds.

This same recording technique was used from the air in March, 1955. Sonobuoys, all of which worked successfully, were dropped from a low altitude at the positions of A′, B, and B′ in Figure 3. By switching receiver channels transmissions from pairs of buoys were recorded much in the same manner as previously described. No volcanic sounds were recorded; Bárcena had been dead since the previous August. However fish noises were recorded and the method was proved feasible from the air.

Underwater acoustic observations in Shelikof Strait—Mt. Trident volcano became active in

February, 1953 [*Snyder*, 1954]. From June to September the activity consisted of a quiet extrusion of lava and steady, moderately vigorous steaming [*Muller*, *Juhle*, and *Coulter*, 1954].

A very brief survey was made in Shelikof Strait (Fig. 1) on August 20, 1953, by the junior author, during a short stopover after he had left the Scripps Trans-Pacific Expedition in Adak, Alaska. An unsuccessful attempt was made to determine if audio energy produced from nearby Mt. Trident, or other volcanoes in the Valley of Ten Thousand Smokes, was present in the water of the Strait between the northwestern tip of Kodiak Island and the Katmai National Monument on the Alaskan peninsula. In order that the recordings could be correlated with the activity of Mt. Trident the late Werner Juhle and others observed the Volcano during the time of the survey.

A three station listening survey was made across Shelikof Strait on the M/V *Dennis Winn*, during the night of August 20, from Cape Raspberry on western Raspberry Island to Cape Ugyak, Kukak Bay, in eastern Katmai National Monument. The distance to Mt. Trident varied from 53 nautical miles, first station, to 34 miles, third station. All stations were made in approximately 100 fm of water at a hydrophone depth of 100 ft. The average recording time at each station was 21 minutes. While recording, the tape was only partly monitored by earphone and, since the recorder did not have a play-back mechanism, the tapes were later played back in the laboratory at Scripps.

No noises attributable to volcanic action were heard despite ideal weather conditions and a completely silent ship during the recording periods. According to a radio message received later from the party observing Mt. Trident, the Volcano emitted no noise during the recording periods and was not very active. However, seven hours after the survey was completed six loud rumbles, due to steam explosions, were produced within three hours, three of which were spaced only ten minutes apart. Unfortunately the available time and supply of tape did not permit the recording periods to be extended. In an operation of this kind it appears that recordings must definitely be made over much longer periods of time and that play-back equipment should be available in the field in order to permit re-using any tape on which wanted sounds had not been recorded.

Analysis and origin of sounds recorded at Bârcena Volcano—Two kinds of volcanic sounds have been recorded at Bárcena. The first, a hissing sound heard and recorded on several occasions, we believe to have been produced when the sea came in contact with hot lava. A second, less likely, explanation is that it may have been produced by the shifting of blocks of lava as the flow settled into the unconsolidated ash beneath the delta. A similar airborne hissing-grinding sound also was heard when standing next to the moving lava flow (see Table 2).

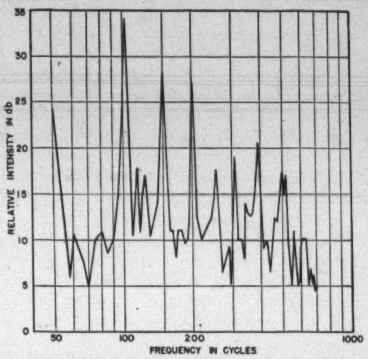


FIG. 4 – Acoustic spectrum of the rumble from Bárcena Volcano recorded November 15, 1952; arbitrary reference level of 0.015 volt to analyser is equal to 0 db

The low-frequency rumble, recorded in November, 1952, and September, 1953, has been studied by means of a detailed frequency analysis, illustrated in simplified graphic form (Fig. 4). The original frequency analysis, 49–800 cycles, was obtained from a Western Electric RA 1437 frequency spectrum analyser which is a scanning filter system of adjustable band width. The acoustic signal shows distinct energy maxima at 49, 103, 150, 203, 257, and 309 cycles. Little energy exists above 550 cycles. There is a strong harmonic progression of approximately 50 cycles. However, because of the attenuation of the sonobuoy hydrophone it is possible that 49 rather than 103 cycles represents the fundamental frequency of the rumble. The background noise level is below the arbitrary reference level (0 db) of 0.015 volts to the analyser. It is difficult to assign a special pitch to the rumble; a pitch of 125 cycles is a close approximation.

Few detailed frequency analyses have been made of biological and other sounds occurring in the ocean. Consequently we are unable at this time to make a detailed comparison with selected naturally occurring noises. For a discussion of various noises in the ocean the reader is referred to the paper by *Knudsen*, *Alford*, and *Emling* [1948].

Dobrin [1947, p. 22] graphed audio frequency against sound pressure for noises produced by six fish. His graphs show frequency maxima between approximately 200 and 500 cycles, intensity attenuation both above and below the maxima, and comparatively little energy below 100 cycles. From a U. S. Navy recording of the isolated 'boob' produced by the toadfish *Opsanus tau* a detailed frequency analysis was prepared for comparative purposes. There is little in common between the two analyses.

As far as we can tell qualitatively there does not appear to be any similarity between the volcanic sounds, sounds of known biological origin, and other sounds present in the ocean such as wave and surf noises. This is confirmed by experts in marine biology acoustics Martin W. Johnson and Marie P. Fish and by Naval personnel in the field of underwater sound all of whom report they have never heard similar sounds.

The rumble has not been correlated with visible activity. A possible explanation is that it may be related to the movement, or escape, of gas in the magma conduit or crater lava.

Summary and discussion—Sonobuoy and hydrophone investigations from ship and plane have demonstrated that audio energy generated by Bárcena Volcano could often be detected by underwater listening equipment when no sounds could be heard by observers stationed on or near the volcano at approximately the same time. This is undoubtedly because sound energy, especially in the low frequencies, is much more readily propagated in water than in air.

Although we have been concerned with underwater volcanic acoustics it should be apparent that terrestrial studies using tape recorders can be conducted by substituting sensitive contact microphones for hydrophones. Doak Cox (personal communication) has suggested that immersing a hydrophone in the water of a well near an active volcano might provide a better impedance match than direct coupling with the ground. For acoustic triangulation, using receiving equipment similar to that described in this paper, several microphones could be remotely placed in the field, connected to a central receiving station by either radio or transmission lines. Investigations of acoustic energy, especially when made for extended periods of time, may prove to be a valuable adjunct to seismic studies, the best present method of investigating the internal functions of a volcano.

We have made only qualitative measurements at Bárcena, but it should be possible to make quantitative measurements of volcanic sound energy both from land and sea.

Additional study of volcanic acoustics is highly desirable. The eminent volcanologist Frank A. Perret, the first pioneer in volcanic acoustic research, after nearly half a century of study summarized his opinion [*Perret*, 1950, p. 141] shortly before his death, by writing, "Submarine detection by microphone devices is now well known, and I consider subterranean auscultation vitally important to volcanological science."

Acknowledgments—This paper represents results of research carried out by the University of California in part under contract with the Office of Naval Research. The flights to San Benedicto Island were made for the most part with Office of Naval Research sponsorship and the assistance of Photographic Squadron 61, U. S. Navy, as part of the scientific study of Bárcena Volcano. We acknowledge with appreciation the assistance of the many people who have aided us in this study, in particular to Woodrow Krieger, for transportation on his yacht *Observer*, and Captains Zamora of the *Observer*, Perriera of the *Star of the Sea*, Valin of the *Columbia*, and Dall of the *Dennis Winn*. The Shelikof Strait survey was made possible thanks to the excellent cooperation of the 30th Engineer Base Topographic Battalion, U. S. Army, which made available their chartered U. S. Fish and Wildlife ship *Dennis Winn*. The frequency analyses were kindly made for the authors by S. H. Sessions and T. H. Wells of the U. S. Navy Electronics Laboratory. A preliminary copy of the manuscript was read by Gordon Macdonald, Howard Powers, George Snyder, Ray Wilcox, and Howel Williams, who offered helpful suggestions.

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Report of the Committee on Runoff, 1954–1955

VEN TE CHOW, *Chairman*

HENRY W. ANDERSON
GORDON R. AYER
BERTRAM S. BARNES
HAROLD W. HOBBS
ROY E. OLTMAN
ANTHONY J. POLOS
W. D. POTTER
JAY C. PYLE
GEORGE R. SHANKLIN

During the year 1954–1955 the Committee on Runoff achieved four major tasks: (1) A survey of the present status and development of runoff research activities of the agencies with which the Committee members are associated; (2) sending out letters to authors of selected papers on runoff that have appeared in the current *Transactions*, asking for progress reports on any additional work that might have been completed on these subjects; (3) sending letters of solicitation for discussions to the qualified persons that have been suggested by members of the Committee in the past year; and (4) compilation of a list of outstanding papers on runoff published in recent years. Owing to the limitation of space alloted for publication, only the list of publications compiled under (4) is reported herewith.

CURRENT LITERATURE ON RUNOFF

The following is a list of papers on runoff published after 1950, which do not appear in the *Transactions*. It includes those papers which are available to and are considered significant by the Committee members. It is to be noted that annotated bibliography on runoff from 1941 to 1950 has been compiled by the Union, in cooperation with Federal Inter-Agency River Basin Committee, and published as Annotated Bibliography on Hydrology, 1941–1950, *Notes on Hydrologic Activities, Bulletin* 5, by U. S. Government Printing Office, June 1952.

GENERAL RAINFALL-RUNOFF RELATIONSHIP

Relation between Daily Rainfall and Flow of the River Shin, by Roderick Hugh MacDonald, *Proceedings, Institution of Civil Engineers*, pt. 3, v. 1, pp. 1–38, spring 1952. Discusses a method of deriving the daily flow from the daily rainfall, based on consideration of the recession curve of daily flow at times of no rain. The method is shown to be of general application and explains several well-known features of river behavior.

Les Crues Italiennes Catastrophiques de l'Automne 1951 (The Disastrous Italian Floods of Autumn 1951) by M. Parde, *La Houille Blanche*, no. 2, Apr. 1952, pp. 319–327. A hydrologic description of the storm and the resulting big flood in Po River.

Notes on Relationship between Rainfall and Runoff, by D. F. Roberts, *Transactions, South African Institution of Civil Engineers*, v. 2, no. 11, pp. 269–278, Nov. 1952. Lists number of gaging stations in South Africa with rainfall and runoff data and suggests methods for dividing Union into runoff zones. Graphs are given to indicate limits between which value of runoff must fall for any particular zone and for any value of mean annual rainfall. Several formulas are suggested.

Estimation of Reliable Yield of Catchment by Correlation of Rainfall and Runoff, by F. Law, *Journal, Institution of Water Engineers*, v. 7, no. 3, pp. 273–293, May, 1953. A method is proposed which is based on correlation between runoff from catchment and rain which has fallen upon it in same period, as indicated by readings of one or more rain gages. Variability of rainfall, stages of the method, etc. are discussed.

Rainfall, Runoff, and Storage: Elan and Clearwen Gathering Grounds, by C. A. Risbridger and W. H. Godfrey, *Proceedings, Institution of Civil Engineers*, pt. 3, v. 3, no. 2, pp. 345–388, Aug. 1954. Analyzes hydrologic features of the catchment, most of the records being expressed in terms of the long-average rainfall so that they can be readily applied to other areas. A curve of 'reliability of runoff' is developed for showing probable extremes of runoff in any consecutive period up to 36 months' duration and demonstrating the storage required to equalize the runoff over the driest three consecutive years.

HYDROGRAPH STUDIES

On Algebraic Solution of Unit Hydrograph for Runoff Resulting Out of Composite Rainfall, by G. Sinha, *Irrigation and Power Journal*, Central Board of Irrigation and Power, India, v. 8, no. 3, July 1951, pp. 459–466. Derivation of equations and analysis of runoff by unit hydrograph.

Notes on Flood Hydrographs, by W. F. Gilbert, *Journal, Institution of Water Engineers*, v. 6, pp. 165–184, 1952. Explains the effects on the flood hydrograph of various types of flood storage; the effect of protecting natural flood lands from inundation; and methods of estimating the maximum flood flow from recorded flood hydrographs.

Unitgraph Procedures, by B. S. Barnes, Hydrology Branch, Division of Project Planning, U. S. Bureau of Reclamation, 48 pp., Nov. 1952. A comprehensive discussion of methods of unit hydrograph in regular practice or experimental use by the Hydrology Branch, Division of Project Planning.

Le Calcul des Crues par les Hydrogrammes Unitaires, (Flood Calculations by the Unit Hydrograph Method) by P. Cappus, *La Houille Blanche*, Special no. A, Mar.–Apr. 1953, pp. 159–167. The unit hydrograph method is studied by applying it to an experimental plot at Alrance.

Contribution à l'Étude des Crues (A Contribution to the Study of Floods) by J. Larrieu, *La Houille Blanche*, Special no. B, Nov. 1954, pp. 725–730. Describes a method to derive the flood hydrograph from known rainfall. The method was applied to the Durance River basin in France and the results proved very encouraging.

Estimation of Runoff Discharges

Note sur l'Estimation des Débits de Crues (Estimation of Flood Flows), by G. Morlat, *La Houille Blanche*, v. 6, Special no. B, pp. 663–678, Oct. 1951. Discusses various methods of computing flood intensities: use of empirical formulas; statistical and analytical methods, possibility of rainfall analysis, etc.

Predicting the Runoff from Storm Rainfall, by M. A. Kohler and R. K. Linsley, *Research Paper 34*, U. S. Weather Bureau, Sept. 1951. Describes the technique used at the River Forecast Centers of the U. S. Weather Bureau for evaluating the effect of season, antecedent conditions, duration of rainfall and rainfall amount in determining the portion of the rainfall contributing to storm runoff.

Method of Determining Maximum Flood Discharge from the Relation to the Area of the Watershed, by M. F. Sribnyi, *Russian Scientific Academy News* (*Izv. AN SSSR Otd. Tech. Nauk*), no. 1, pp. 140–152, Jan. 1952. Describes the brief history and the development of hydrology in Russia. At the present time, methods involving basin characteristics and climatological effects are used in place of the old Kochrin approach. Suggests an organization to study the problems of flood discharge in a large scale. A formula developed by the Russian Academy of Sciences is presented.

Choix du Débit de Crue pour Lequel il Convient de Prévoir les Ouvrages Évacuateurs d'un Barrage (Choice of the Flood Discharge for Which the Spillway Structures of a Dam Should Be Designed) by J. Duffaut, *La Houille Blanche*, Special no. B, July 1952, pp. 506–512. Proposes to substitute the notion of frequency in space for the notion of frequency in time. Veritable hydrologic catastrophes observed in a great number of small watersheds can give valuable information on the maximum floods in few large watersheds.

Flood Intensities and Frequencies on British Catchments, by G. Bransby William, *Engineer*, London, v. 194, no. 5039, pp. 247–251, Aug. 22, 1952. Describes various methods of computing flood intensities and also a method of constructing synthetic basic hydrographs in the absence of sufficient stream flow and rainfall records.

Peak Discharge for Highway Drainage Design, by Carl F. Izzard, *Transactions, American Society of Civil Engineers*, v. 119, pp. 1005–1024, 1954. Shows that, by developing regional flood curves, the peak rate of runoff on a stream can be estimated for a given frequency, whether or not stream gaging records are available for that particular stream. A graph is included that can be used for estimating peak rates of runoff on small watersheds to aid in culvert design.

Use of Indices in Estimating Peak Rates of Runoff, by W. D. Potter, *Public Roads*, U. S. Bureau of Public Roads, pp. 1–8, Apr. 1954. Describes a procedure which requires the measurement of the principal factors that affect runoff and the determination of their relations to the magnitude and frequency of peak rates.

Watershed Studies

Crue Exceptionnelle sur la Seuge (Exceptional Floods of the Seuge River) by J. Duffaut and P. Avril, *La Houille Blanche*, Special no. A, Mar. 1952, pp. 161–167. Description of a violent flood on June 16, 1951, in the Seuge River, a tributary of the Allier. The magnitude of the flow exceeded the normal design flood for spillways. A flow of 2.5 $m^3/sec\ km^2$ was observed from the 150-km^2 watershed.

Des Covariations Interfluviales, (Interfluvial Covariations) by A. Coutagne, *La Houille Blanche*, v. 6, Special no. A, pp. 279–286, May 1951. Statistical investigations of correlations in hydrometeorology applied to regimes of two watersheds considering average annual and monthly discharges.

Ground-Cover Requirements for Summer-Storm Runoff Control on Aspen Sites in Northern Utah, by R. B. Marston, *Journal of Forestry*, v. 50, no. 4, Apr. 1952, pp. 303–307. Plot study of effects of different amounts of plant and litter cover on overland flow and erosion initiated on upper slopes of 2000 acre Parrish Creek watershed.

Hydrologic Studies of Urban Watersheds: Rainfall and Runoff of Boneyard Creek, Champaign-Urbana, Illinois, by Ven Te Chow, *Civil Engineering Studies, Hydraulic Engineering Series*, no. 2, Dept. of Civil Engineering, University of Illinois. 60 pp., Nov. 1952. A general hydrologic study of an urban watershed which has an effective drainage area of 4.45 mi^2 and a population density of 14 persons per acre. Runoff is measured by a recording stream gage and precipitation by a net work of eleven raingages. Major studies include: frequency analysis of rainfall, areal distribution of storms, derivation of unit hydrograph, and determination of the consumptive use of water.

Stream-Flow Reactions of a Fire-Damaged Watershed, by J. D. Sinclair and E. L. Hamilton, *Proceedings, American Society of Civil Engineers*, v. 81, Separate 629, 17 pp., Feb. 1955. Records of rainfall and stream flow from the partly burned watershed in the San Gabriel Mountains of southern California and from a comparable unburned drainage area, before and after the December, 1953 fire, were analyzed. The analyses showed that peak flows and storm discharges from the damaged watershed were greatly increased by the effects of the fire.

Runoff Measurement

Computation of Peak Discharge at Contractions, by C. E. Kindsvater, R. W. Carter, and H. J. Tracy, *U. S. Geological Survey Circular 284*, 34 pp., 1953. Describes a method for determining peak discharge at abrupt contractions from a survey of high-water marks and characteristics of the channel.

Measuring Runoff Rates with Rectangular Highway Culverts, by W. O. Ree and F. R. Crow, Oklahoma Agricultural Experiment Station, *Technical Bulletin T-51*, Nov. 1954. Describes a simple and relatively inexpensive gaging station for use by engineers desiring to obtain runoff data on specific areas. The station described makes use of existing highway culverts, thereby considerably reducing the cost.

Statistical Methods

Some New Statistical Techniques in Geophysics, by Arnold Court, *Advances in Geophysics*, v. 1, Academic

Press, pp. 45–85, 1952. A concise treatment of recent development in hydrologic statistics is presented.

Low Flow Characteristics of Streams by C. J. Velz and John J. Gannon, paper presented at Ohio Water Clinic, Columbus, Ohio, Feb. 20, 1953, 19 pp. Describes a rational approach to the statistical evaluation of low flow characteristics of streams from the theory of extreme values. Drought flow is defined and its probability discussed.

Handbook of Statistical Method in Meteorology, by C. E. P. Brooks and N. Carruthers, H. M. Stationery Office, London, 421 pp., 1953. Various statistical methods used in hydrology are included.

Review of Flood Frequency Methods: Final Report of the Subcommittee of the Joint Division Committee on Floods, *Transactions, American Society of Civil Engineers*, v. 118, pp. 1220–1230, 1953. A general discussion and evaluation of flood frequency methods.

Characteristics of Frequency Curves Based on a Theoretical 1000-Year Record, by M. A. Benson, U. S. Geological Survey, Water Resources Division, 21 pp., Aug. 1952. Contains a summary of the procedures followed and the results obtained in analyzing a 'perfect 1000-year record' of maximum annual peak floods. Confirms by actual computation the use of 2.33 years as the recurrence interval for the mean annual flood for a straight-line distribution on a Gumbel graph. A study on the variability of results from different periods of record and the principle of composite flood frequency curves are described.

Estimation of Flood Probabilities, by Leo R. Beard, *Proceedings, American Society of Civil Engineers*, v. 80, Separate 438, 21 pp., May 1954. Data of annual maximum mean-daily flows at 159 long-period river measurement stations are analyzed to determine the characteristics of the frequency distributions and the reliability of probability determinations made therefrom. It is shown that the logarithms of the flows are normally distributed, which fact makes applicable to flood-flow data a wealth of statistical procedures and criteria.

Statistical Theory of Drought, by E. J. Gumbel, *Proceedings, American Society of Civil Engineers*, v. 80, Separate 439, 19 pp., May 1954. Analyzes droughts by the asymptotic theory of smallest values of a limited statistical variate. Theory, procedure, and examples are given.

Length of Record and Number of Stations Required in Statistical Analysis of Hydrologic Data, by Shuh-Chai Lee, paper presented to Regional Technical Conference on Water Resources Development, United Nations Economic Commission for Asia and the Far East, May 17–20 1954, Tokyo, Japan. Use is made of the random sampling theory to the problem of 'sample size' of hydrologic data in terms of mean and extreme values. The size of sample needed to estimate mean value of hydrologic data to guarantee a certain desired accuracy in certain degree of certainty is proportional inversely to the square of the percentage of accuracy desired and directly to the square of the Student's *t*-value; it also varies directly as the square of the coefficient of variation. For extreme value estimate, procedure and examples are given.

Some Aspects of Time Series in Hydrology, by G. N. Alexander, *Journal, Institution of Engineers*, Australia, v. 26, no. 9, pp. 188–198, Sept. 1954. If hydrologic observational data are studied in the sequence in which they are obtained, then such studies are termed 'time series' analyses. In most statistical theories the sequence is irrelevant and the study centers on the frequency distribution of the observations, which is obtained by arranging them in order of magnitude. In such cases, the distribution of extreme values is often concerned. This paper gives the principle, procedure, and examples of the time-series problem in hydrology.

The Log-Probability Law and Its Engineering Applications, by Ven Te Chow, *Proceedings, American Society of Civil Engineers*, v. 80, Separate 536, 25 pp., Nov. 1954. A theoretical treatment of the log-probability law, including applications mainly to runoff data, derivation of characteristic values, revision of Hazen's table, verification of extreme value law as a special case of log-probability law, and a new method of fitting data. Eleven discussions of this paper are given in Proceedings—Separates: 665, pp. 21–41, April 1955; 709, pp. 11–27, June 1955; and 719, pp. 13–15, June 1955.

Extending Flood-Frequency Graphs by Comparison with Rainfall, by W. B. Langbein, Water Resources Division, U. S. Geological Survey, open-file manuscript, Feb. 16, 1955. Describes a method which assumes that the probability of a given flood is the product of the probabilities of the independent events, chiefly; the storm rainfall and the antecedent conditions. The purpose of this study is to demonstrate the physical validity of the use of rainfall data to extend a flood frequency graph in those areas where stream-flow records are relatively short and daily discharges are of practical value.

Runoff Forecasting

Forecast and Records of Floods in Glen Cannich in 1947, by P. O. Wolf, *Journal, Institution of Water Engineers*, v. 6, no. 4, July 1952, pp. 298–316. Describes four stages of work on the problem of flood runoff from the small and steep catchment of the River Cannich, including contractor's forecast, observations of a heavy flood and its analysis, review of contractor's forecast, and a probability study.

Les Crues de la Seine à Paris (The Seine Floods at Paris) by B. Gaspard, *La Houille Blanche*, Special No. A, May 1954, pp. 278–286. A critical study of the flood characters and forecasting methods.

Flood Frequencies Derived from River-Forecasting Procedures, by Ralph F. Kresge and Tor. J. Nordenson, *Proceedings, American Society of Civil Engineers*, v. 81, Separate 630, 16 pp., Feb. 1955. Demonstrates the feasibility of using long-term precipitation observations to extend runoff records in order to develop more reliable annual peak discharge frequency curves.

The following is a list of reports on runoff forecasting prepared by the Technical Staff of the Water Management Subcommittee, Columbia Basin Inter-Agency Committee. The Technical Staff is a work group responsible to the Water Management Subcommittee, and performs such tasks as designated by the Water Management Subcommittee. Besides the study of forecasting procedures, the Technical Staff also considers operation of the hydrometeorological reporting network and project operation as its immediate

problems. At present, the staff members are represented by Bonneville Power Administration, Bureau of Reclamation, Corps of Engineers, and Weather Bureau.

Review of Procedures for Forecasting Inflow to Hungry Horse Reservoir, Montana, 27 pp., June 1953.

Review of Procedures for Forecasting Seasonal Runoff of Boise River above Diversion Dam, Idaho, 51 pp., Jan. 1954.

Recommended Reservoir Storage Adjustments to Seasonal Runoff Volume Forecasts in the Columbia River Basin, 19 pp., Feb. 1954.

Recommended Base Period for Comparing Runoff Forecasts and Related Hydrologic Data in the Columbia River Basin, 15 pp., July 1954.

Review of Procedures for Forecasting Seasonal Runoff of Columbia River near the Dalles, Oregon, 62 pp., Aug. 1954.

Use of 30-day Weather Outlook in Forecasting Runoff in the Columbia River Basin, 14 pp., Jan. 1955.

Publication on Flood Frequency Data in the United States

The following are publications on flood-frequency data in the United States, arranged in order of the date of publication. Three statewide reports are due to be published in the near future: those for Connecticut, Nebraska, and Missouri. That of Nebraska will be published by the State; while the other two as U. S. Geological Survey Circulars. A report for North Carolina is in the final stages, and will come out as a State report.

(1) Floods in the United States, Magnitude and Frequency, by C. S. Jarvis and others, *Water Supply Paper 771*, U. S. Geological Survey, 497 pp., 1936.

(2) Magnitude and Frequency of Floods on Illinois Streams, by George W. Pickels, *Engineering Experiment Station Bulletin 296*, University of Illinois, 59 pp., Aug. 1937.

(3) Flood Flows on Mississippi Streams, by Horace W. Wood, Jr., *Bulletin 30*, University of Missouri Engineering Experiment Station, 86 pp., 1942.

(4) Floods in Ohio, Magnitude and Frequency, by William P. Cross, *Bulletin 7*, Ohio Water Resources Board in cooperation with the U. S. Geological Survey, Columbus, Ohio, 154 pp., Oct. 1946.

(5) Magnitude and Frequency of Floods in Minnesota, by C. H. Prior, *Bulletin 1*, Minnesota Department of Conservation, Division of Waters, Minnesota, 1949.

(6) Magnitude and Frequency of Floods in the Columbia River Basin, by S. E. Rantz and H. C. Riggs, *U. S. Geological Survey Water-Supply Paper 1080*, pp. 317–469, 1949.

(7) Floods in Georgia – Frequency and Magnitude, by R. W. Carter, prepared by U. S. Geological Survey in cooperation with the State Highway Department of Georgia and Georgia Department of Mines, Mining, and Geology, *U. S. Geological Survey Circular 100*, 127 pp., March 1951.

(8) Floods in Western Washington – Frequency and Magnitude in Relation to Drainage Basin Characteristics, by G. S. Bodhaine and W. H. Robinson, *U. S. Geological Survey Circular 191*, 124 pp., 1952.

(9) Floods in Youghiogheny and Kiskiminetas River Basins, Pennsylvania and Maryland – Frequency and Magnitude, *U. S. Geological Survey Circular 204*, 22 pp., 1952.

(10) Floods in Louisiana – Magnitude and Frequency, by J. S. Cragwall, Jr., prepared by U. S. Geological Survey in cooperation with the State of Louisiana Department of Highways, 281 pp., Dec. 1952.

(11) Iowa Floods – Magnitude and Frequency, by H. H. Schwob, *Bulletin 1*, Iowa Highway Research Board, 1953.

(12) Floods in Alabama – Magnitude and Frequency, by L. B. Peirce, U. S. Geological Survey prepared in cooperation with the Alabama State Highway Department, *U. S. Geological Survey Circular 342*, 105 pp., 1954.

(13) Floods in Illinois – Magnitude and Frequency, by William D. Mitchell, prepared in cooperation with the U. S. Geological Survey, and issued by Division of Waterways, Department of Public Works and Buildings, State of Illinois, 386 pp., 1954.

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Letter to the Editor

Note on Gougenheim's Method of Azimuth Lines

In the August 1955 issue of the *Transactions* appeared a review of Traité de Géodésie by Pierre Tardi and Georges Laclavère in which the reviewer, former Editor for Geodesy, Alfred D. Sollins, makes the following reference: "Notable among these [miscellaneous methods for position determination] is the azimuth method proposed by A. Gougenheim and which has been advocated also by Canadian geodesists for work in high latitudes." The Editor has received in this connection a communication from André Gougenheim, Hydrographic Engineer in Chief of the French Navy, annotating this statement and we take the liberty of translating and publishing pertinent portions of his letter, as follows.

. . . I should like, however, to point out the differences between these two methods.

In the first place the procedure I investigated under the name 'method of azimuth lines' [droites d'azimut] is clearly anterior. It was presented to the Academy of Sciences of Paris by André Danjon on October 9, 1950 [C.-R. v. 231, pp. 684–686] in which it is specifically stated that the method is particularly advantageous at high latitudes.

Furthermore, the observation equation which involves the three unknowns (latitude ϕ, clock correction C_p, and the azimuth V with respect to the zero of the horizontal circle) is the formula known in spherical trigonometry as the law of cotangents. In order to solve the system of excessive equations resulting from the various observations, it is convenient to linearize them by means of an approximated solution and choosing as new variables the differences $\Delta\phi$, ΔC_p, ΔV between the true values and the approximations.

One can stop with this system of linear equations and solve it by the least-squares method. This is the procedure adopted by geodesists in Canada.

The method of azimuth lines goes further. It replaces in the linearized equation the unknown ΔV by a mixed unknown $\sin \phi_0 \Delta C_p - \Delta V$, so that, designating by Z an approximated value of the azimuth of the star and by h its approximated altitude, the first member of the equation becomes

$$\Delta\phi \sin Z - (\Delta C_p \cos \phi_0) \cos Z + \cot h \, (\sin \phi_0 \Delta C_p - \Delta V)$$

The second member is the product of cot h times the difference between two approximations of the star's azimuth, one obtained by computation and the other from the reading of the horizontal circle.

If all the stars are observed at about the same altitude, the coefficient cot h of the third unknown remains constant and one can therefore use a graphical method of solution with straight lines enveloping a circumference (whence the name) analogous to that used for treating observations of equal altitude (specifically the prismatic astrolabe). The only difference is that the radius of the circle represents the third unknown and not, as in the case of the method of equal altitudes, the correction to the assumed altitude, which is of no practical interest.

Moreover, if it is preferred to use least-squares rather than a graphical solution, the computations are simplified due to the fact that the coefficients of the unknowns are sin Z, cos Z and 1 (taking as the third unknown the quantity

$$\cot h \, (\sin \phi_0 \Delta C_p - \Delta V)).$$

Attention is also called to my paper entitled Théorie et pratique de la méthode des droites d'azimut in *Bulletin Géodésique*, no. 32, pages 155–184, June 1954.

A. Gougenheim

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Discussion of "Some Factors Affecting Rates of Sedimentation in the Columbia River Basin"

ELLIOTT M. FLAXMAN AND ROBERT L. HOBBA

[*Trans.*, **36**, 293–303, 1955]

Harold E. Thomas (U. S. Geological Survey, Salt Lake City, Utah)—Hydrologists are generally aware of the number and complexity of the variables that are encountered in all aspects of hydrology, and the great difficulty of analyzing these factors quantitatively because of inadequacy of basic data. Because of limitations in funds, time, or scientific manpower, it is likely that the basic data will generally be less than the hydrologist's hopes. In this predicament, many students have sought methods whereby it might be possible to determine the approximate effects of various factors, on the basis of meager available information. The authors, by using statistical methods of analysis, have pointed out one way that may well be rewarding in studies of other aspects of hydrology where little basic information is available.

Statistical analyses can be checked to show the order of accuracy of their results, and the authors point out that the standard error is too high to permit accurate determinations of the rates of sedimentation for specific ponds; thus the findings of this paper could not be used for forecasting sedimentation in ponds under construction or proposed. But I would think it desirable to qualify for the scanning reader the statement that five factors account for 80 pct of the variation in observed sediment in the stockponds studied. I am particularly dubious about the factor of "original storage capacity per square mile," which accounts for as much of the variation as the other four factors combined. As the authors point out, this is a measure of trap efficiency rather than natural sedimentation, and it reminds me unhappily of my discomfiture in a college chemistry course, when I continued with a quantitative analysis after a beaker had boiled over.

My principal doubts as to the other significant factors found by the authors stem from my acquaintance with fields of hydrology other than sedimentation. These factors have been determined without recourse to data on runoff or on water-transmitting characteristics of the soils and underlying rocks of the watersheds from which the sediment is derived. Yet, sediment is obviously related fundamentally to runoff, and the soil and underlying rocks of a watershed are not only the sources of the sediment, but they also are factors that determine what proportion of the precipitation will move over the surface, and what proportion will infiltrate into the ground. All the water that moves laterally from a point of precipitation moves either as runoff or as ground water, depending upon the permeabilities of the rock materials. Thus, although sedimentology and ground-water hydrology may appear to be widely separated fields, the water-bearing characteristics of rock materials may throw some light on the characteristics of the runoff that is responsible for the sediment.

The authors report that neither the variations in soils nor the topography have any statistical significance with respect to sediment accumulation. However, their stockponds 28 to 34 inclusive, and 37 are in the basins of the John Day River and Deschutes River, whose contrasting runoff characteristics have been described and explained by *Piper* [1948, p. 516]:

> "Those contrasts in the general runoff characteristics of the John Day and Deschutes Basins are all the more striking because the two basins are contiguous and have about the same proportion of forest cover, also because, excepting the westernmost part of the Deschutes Basin, the two basins are alike in mean altitude, in relief, and in climatic variables. The two are unlike in geologic features which determine their average infiltration capacities; that of the John Day Basin is relatively small, whereas that of the Deschutes Basin (especially certain parts of the basin) is uncommonly large."

In general for the 38 stock ponds there appears to be a degree of relation between average annual yield of sediment per square mile, and types of rocks cropping out in the drainage basin. Thus ponds 1–5, 24, and 26, with drainage basins underlain by Miocene lavas and associated gravels, have a low ratio of sediment yield; these rocks are permeable enough to yield large quantities of water to wells in many places. The drainage basins underlain by lake beds and other continental deposits, as exemplified by ponds 6–9 and 19–22, have a somewhat higher rate of sediment yield. The highest rates of sediment yield, however, come

from drainage basins having a mantle of easily erodible Palouse silt (ponds 11–18). The average annual sediment yields in the 38 ponds, as listed in the authors' Table 2, show a far more striking geographic grouping, or, more properly, geologic grouping, than might be expected from the factors that are deduced to be primarily responsible for these variations.

Several of the significant factors as developed by the authors appear to be indirect expressions of more fundamental factors in sedimentation. Thus, the apparent effect of size of drainage area may well be a reflection of the variations in geology, by reason of the locations of the ponds selected. Several of the largest drainage basins (areas ranging from 700 to 4143 acres) are underlain by Miocene lavas and associated continental deposits, and all have low rates of sediment production. By contrast, the eight smallest drainage basins (with an aggregate area of 102 acres) are underlain in part by Palouse silt, and generally yield sediment at high rates.

The relation of annual precipitation to sediment accumulation apparently is an indirect expression of the controlling factor of runoff in sediment accumulation. One might expect the correlation of precipitation with runoff in small watersheds tributary to stock ponds to be more direct than in drainage basins covering thousands of square miles. In these larger drainage basins the secular variations in precipitation and runoff rarely exhibit a straightline relationship. Correlations from one basin to another depend upon the similarity of topography, geology, soil, and cover of the basins. In drainage basins with contrasting runoff characteristics resulting from geologic characteristics, as for example the John Day and Deschutes basins [*Piper*, 1948], close correlation between sediment accumulation and annual precipitation would be unlikely.

In the area considered by the authors, the average annual precipitation ranges from six to more than 60 inches, or from arid to humid. Because the annual precipitation in arid regions is characteristically less than the potential evapotranspiration, the annual precipitation is a very inadequate index of runoff. This has been demonstrated in recent studies of the Cheyenne River basin in Wyoming, where average annual precipitation of about 17.4 inches in 1944–50 produced only 21 pct of the runoff that had resulted from approximately the same average annual precipitation in 1915–20 [*Culler* and *Peterson*, 1953]. The reduced runoff was attributed by many to the 9000 stock ponds that had been constructed in the basin since 1930, but recent studies indicate that runoff is dependent primarily upon precipitation intensity rather than upon annual precipitation.

The amount of land subject to erosion may be partly a result of man's activities, but it also may be an expression of the geologic characteristics of the drainage basin. Certainly a basin with surficial materials permeable enough to permit rapid infiltration of water from intense storms is likely to show less evidence of erosion than a basin where soils are impermeable enough to cause overland runoff from similar storms. *King* and *Mace* [1953] have found that sediment-production rates from impermeable shales in the San Rafael Swell of Utah are higher than from sands and friable sandstones, although the sands are more easily erodible.

In conclusion, it is recognized that multiple correlation analysis provides a means for drawing significant conclusions from a relatively limited amount of data, and the standard error indicates the limitations of those conclusions. However, there is danger in using statistical methods as a substitute for essential data. It is doubted that the sediment accumulation in reservoirs can be analyzed adequately without recourse to data on runoff and on the capabilities of water movement through the soils and underlying rocks of the drainage basin.

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Elliott M. Flaxman (Soil Conservation Service, Portland, Oregon) and *Robert L. Hobba* (U. S. Forest Service, Portland, Oregon; Authors' closure) —The standard error of estimate in our analysis corresponds to the standard deviation in an ordinary set of statistics, and it gives an estimate of the variation of any single observation around the sample average. If one were interested in forecasting sedimentation for ponds under construction or for those proposed, the standard error of estimate would give an approximate value for the error of the forecast. However, as always in regression, the data may be incompetent to furnish evidence of trend beyond their own range. To be useful, extrapolation requires extensive knowledge and clear thinking on the part of the

forecaster. In our kind of work, however, we were interested in a tabulation of rates of sedimentation which were actually observed, and another tabulation of calculated rates of sedimentation with the magnitudes changed by land-use practices. For this purpose the estimate of error is a statistic corresponding to the standard error of an average; the standard error of estimate divided by the square root of the number of observations. This error in our case is quite reasonable because of the large amount of variation which has been explained by the analysis.

Thomas' reasons for doubting the factor of "original storage capacity per square mile," and his simile to the chemical analysis, are not quite clear to us. This variable does not account for as much of the variation as the other four variables combined, as he states, but does account for 39 pct of the explained variation. The other variables account for the remaining 61 pct of the explained variation. The authors believe it would require more than subjective reasoning to delete this highly significant factor from the regression equation.

Thomas' discussion of the need for indices of rainfall intensity, runoff, soils, and geology is excellent and well taken. We agree, that when it is possible, such factors should be given an opportunity to express their effects separately, and should be tested separately for their efficiency. It is needless to say, that had such reliable data of runoff, rainfall, and geology been available, they would have been used. Our attempt to include indices of rainfall intensity and soil and slope differences as stated in the paper, resulted in tests showing insignificance. This proved to us that considerably more field investigations are needed before these important factors can be adequately accounted for in a correlation analysis. However, we also believe that the significant factors which have been developed also account for a considerable amount of the variation in sediment accumulation, which is attributable to the factors of rainfall intensity, runoff, and geology. For example, reservoirs with a small storage capacity per square mile are constructed in this area when limited runoff is anticipated, and reservoirs with a large storage capacity per square mile when considerable runoff is expected. Of the possible combinations of causal factors which could be used, the problem consisted largely in determining the way several factors act together in their influence on sediment production. Of first concern was the selection of those major factors influencing sediment production, for which applicable records were available for the particular areas, and the utilization of these records in a manner which would result in the most satisfactory equation. It was pointed out in our paper that more precise information on the effect of variables could be obtained with more data from homogenous areas. With additional data separate equations could be developed to express the effect of independent factors without the overlapping of important influences such as geology and soils.

We would like to add to Thomas' conclusions that multiple correlation analyses, in addition to providing a means for drawing significant conclusions from a relatively limited amount of data, also provides a means for testing the validity of theories and hypotheses. In other words, when we can measure what we are talking about and express it in numbers our knowledge is more valuable.

Discussion of "Were the Carolina Bays Oriented by Gyroscopic Action?"

BY WILLIAM SCHRIEVER

[*Trans.*, **36**, 465–469, 1955]

W. G. Shockley, C. R. Kolb, and W. B. Steinriede (Soils Division, Waterways Experiment Station, Corps of Engineers, U. S. Army, Vicksburg, Miss.; received Oct. 21, 1955)—Judging from the considerable number of papers written on the subject, two theories of the origin of the Carolina Bays appear to be most popular; the meteorite theory of origin advocated by Schriever and the theory recently discussed by *Le Grand* [1953] that they were formed by solution of material at depth. Extensive subsurface exploratory work done by the Corps of Engineers in 1951–52 in portions of the coastal plain region of South Carolina indicates the bays are of solution origin. Various considerations prevent the disclosure of the precise location of this work.

Numerous detailed borings were made in an area marked by literally hundreds of irregular

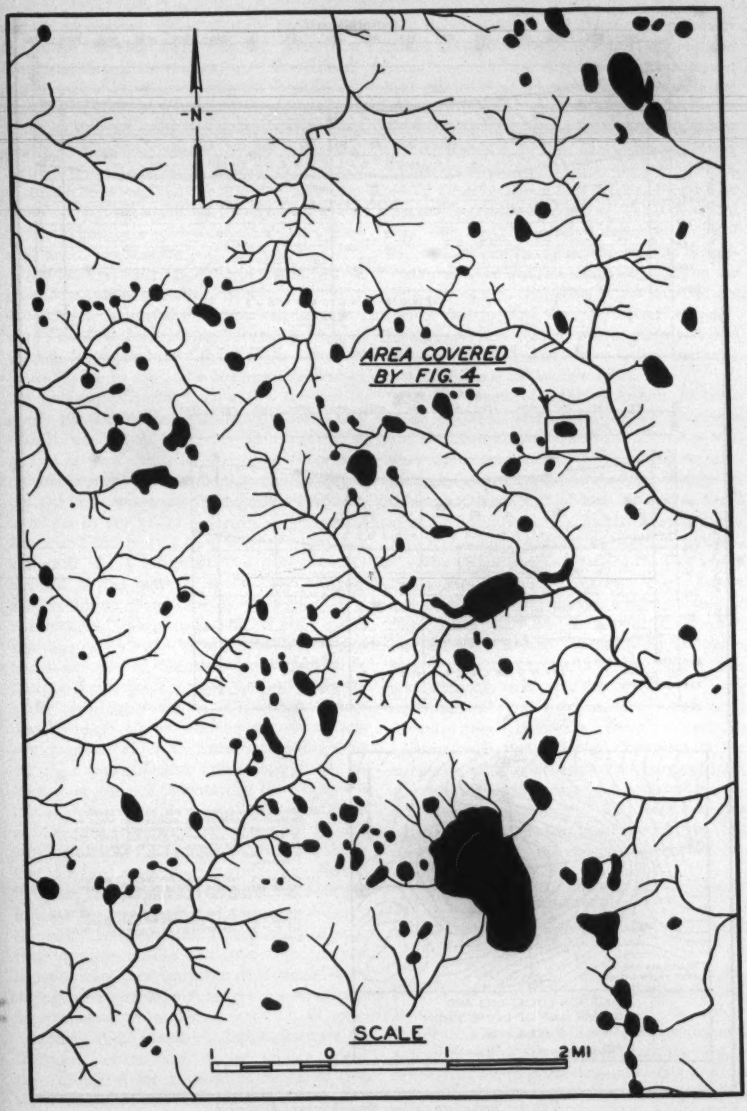

FIG. 3 – *Distribution of depressions and drainage pattern*

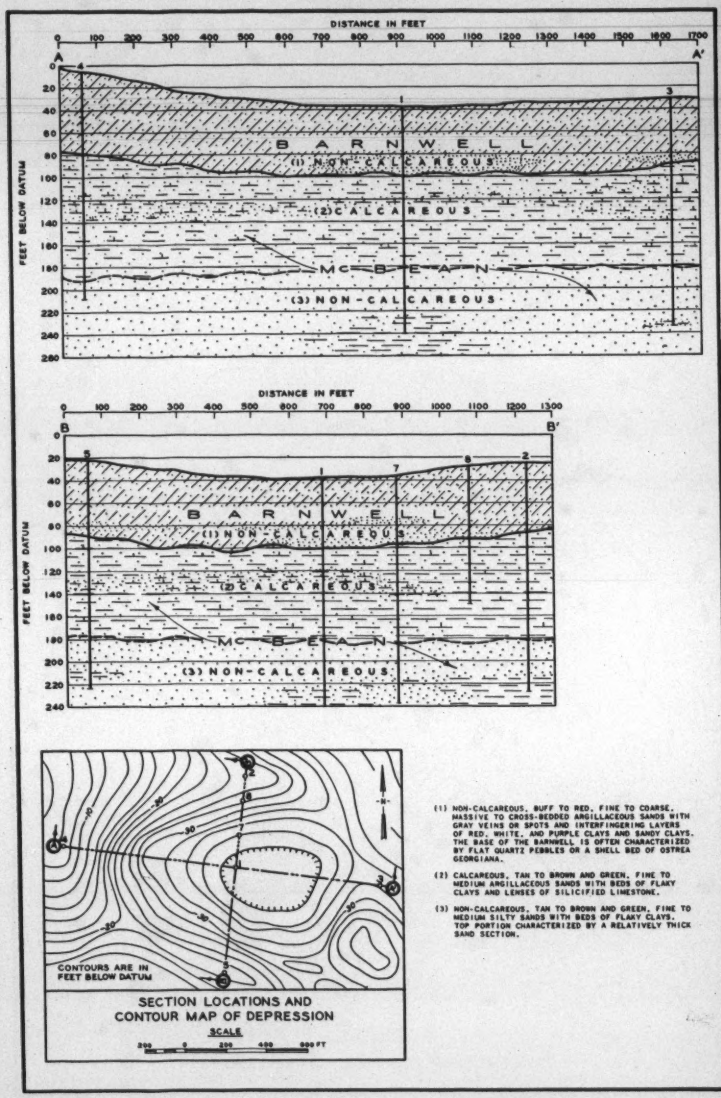
DISTANCE IN FEET
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700
A
A'
FEET BELOW DATUM
BARNWELL
(1) NON-CALCAREOUS
(2) CALCAREOUS
MC-BEAN
(3) NON-CALCAREOUS
DISTANCE IN FEET
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300
B
B'
FEET BELOW DATUM
BARNWELL
(1) NON-CALCAREOUS
(2) CALCAREOUS
MC-BEAN
(3) NON-CALCAREOUS
CONTOURS ARE IN FEET BELOW DATUM
SECTION LOCATIONS AND CONTOUR MAP OF DEPRESSION
SCALE
200 0 200 400 600 FT
(1) NON-CALCAREOUS, BUFF TO RED, FINE TO COARSE, MASSIVE TO CROSS-BEDDED ARGILLACEOUS SANDS WITH GRAY VEINS OR SPOTS AND INTERFINGERING LAYERS OF RED, WHITE, AND PURPLE CLAYS AND SANDY CLAYS. THE BASE OF THE BARNWELL IS OFTEN CHARACTERIZED BY FLAT QUARTZ PEBBLES OR A SHELL BED OF OSTREA GEORGIANA.
(2) CALCAREOUS, TAN TO BROWN AND GREEN, FINE TO MEDIUM ARGILLACEOUS SANDS WITH BEDS OF FLAKY CLAYS AND LENSES OF SILICIFIED LIMESTONE.
(3) NON-CALCAREOUS, TAN TO BROWN AND GREEN, FINE TO MEDIUM SILTY SANDS WITH BEDS OF FLAKY CLAYS. TOP PORTION CHARACTERIZED BY A RELATIVELY THICK SAND SECTION.

FIG. 4 – *Subsurface sections through typical depression*

surface depressions, many of them egg-shaped, typical of Carolina Bays (Fig. 3). Subsurface conditions throughout the area were investigated, and several of the depressions were carefully explored. Stratigraphic boundaries were determined based on detailed study of lithology, fossil, mineral, and calcareous content of the sediments. Sections through one of the depressions having a maximum diameter of 1700 ft and a maximum depth of 18 ft are reproduced on Fig. 4. Several factors indicating a solution origin of the depressions are discussed below.

The numerous borings made in the area have revealed a distinctive calcareous zone from 60 to 160 ft below the surface. The zone extends downward from the base of the Barnwell formation through the upper half of the McBean formation (both Eocene in age). The calcareous content of this zone varies from a fraction of a per cent to nearly 100 pct; the latter occurring in lenses of a slightly argillaceous limestone. The majority of soluble calcium carbonate, however, occurs in a calcareous sand or silty sand. Chemical examinations of undisturbed samples indicate a maximum of 69 pct by dry weight of $CaCO_3$ in these marly strata and 48.7 pct for an average of 20 samples examined. It is estimated that approximately one-half of the material within the calcareous zone is subject to removal by solution.

Porous and cavernous conditions exist within this zone as evidenced by subsurface explorations and observation of this calcareous stratum of the McBean formation where it crops out along the bluffs bordering a nearby river valley. Honeycombed ledges are not uncommon and occasionally caves several feet in diameter are found along the river banks. During drilling operations, the calcareous zone was characterized by considerable loss of drilling mud, low penetration resistances, and occasional drops of several feet of the drill rods. Subsequent grouting was also confined to this zone, and a seal was sometimes very difficult to obtain because of the open character of the formation. The cavernous conditions were found to be usually more prevalent outside the sink areas than within them. The cavernous conditions were found to reach their maximum development where borings were put down along the sloping sides of depressions or on the high ground just adjacent.

Sections A-A′ and B-B′, Fig. 4, illustrate the conditions encountered during drilling operations. Zones of low penetration resistance (two blows per foot or less) were found in Borings 3, 4, and 7. In the case of Boring 3, drill rods dropped suddenly under their own weight from 93.7 to 102.0 ft below datum and about 1200 gallons of drilling mud were lost. There was no drilling mud return from 93.7 ft to the bottom of the hole, and 2640 gallons of mud were used to complete the boring. In Boring 4 the rods settled from depths of 116.7 to 131.1 ft below datum and 900 gallons of drilling mud were lost. There was no drilling mud return from 116.7 ft below datum to the bottom of the hole; about 2800 gallons of mud were required to complete the boring. The rods settled from 120.6 to 127.8 ft below datum in Boring 7 but there was no loss of drilling mud. It is noteworthy that the greatest mud losses were on the periphery of the depression rather than in the center. This suggests that the depressions represent areas where former caverns have collapsed and the overlying strata have settled so that a less cavernous condition now exists.

Surface depressions were abundant in areas where calcareous strata were present; they were rare or absent in areas where the calcareous zone was insignificant in extent, or where it did not exist. Although the calcareous strata were variable in thickness throughout the area, they were found generally to be less thick within the depressions than immediately adjacent to them. In addition, carefully plotted sections showing the base of the Barnwell formation, marked by a decided color and lithologic break, showed a downwarping of this contact below the depressions. Although it was less clearly defined, the base of the calcareous zone in the McBean formation, marked by a thick noncalcareous sand stratum, showed no such downwarping. Both sections A-A′ and B-B′ illustrate this relationship. The most probable explanation is that collapses of caverns in the calcareous zone have bowed the overlying strata and left the underlying strata undisturbed.

It is believed, therefore, that the depressions represent areas where calcareous material has been leached from the soil and the surface has subsided.

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C. Wythe Cooke (U. S. Geological Survey, Washington 25, D. C.; received Oct. 26, 1955)—Under the above title William Schriever discusses a paper of mine [*Cooke*, 1954] in which the peculiar orientation and elliptical shape of certain Carolina bays (swamps) are compared with the hypothetical shapes and orientations deduced for eddies at the same latitudes.

Assuming that a rotating body of a liquid will behave in the same manner as a rotating solid except insofar as its action will be modified by its lack of rigidity, it follows that each particle of the liquid has the same impulse to tilt its plane of rotation as that which causes the gyroscopic properties of a rotating solid. This impulse to tilt appears to be caused by a component of the eddy's centrifugal force acting perpendicular to the axis of the Earth [*Cooke*, 1940, pp. 208–209]. This component varies harmonically with the direction.

The manifestations of this impulse in a liquid are different from but no less distinctive than those of a rigid body. Gyroscopic properties are usually recognized only in solids, but I have applied the term in a broader sense, including both solids and liquids [*Cooke*, 1954, p. 196]. Regarding this, Schriever (p. 465) says: "Gyroscopic action is the property of a rigid body only."

The impulse to tilt the plane of rotation of a rotating liquid (an eddy) directs the initial centrifugal forces into tilted parallel planes, none of which coincides with the surface of the eddy. These forces are divisible into horizontal and vertical components, which vary harmonically in intensity according to the direction of the force.

The horizontal components of the initial centrifugal forces (which are equal) are of variable intensities. They determine the shape of the periphery of the eddy. As they are proportional to the cosine of the angle of inclination of the plane of the initial centrifugal forces, the horizontal periphery of the eddy must be an ellipse.

The vertical components act with or against gravity, a much stronger force. They slightly depress the surface of the eddy on one side of a horizontal line and raise it on the other. The resultant (actual) surface of the eddy becomes a very slightly tilted plane. This surface does not coincide with any of the tilted planes to which reference has been made but is much more nearly horizontal.

By restricting gyroscopic action to rigid bodies, ignoring the comparable properties of liquids, Schriever naturally reaches different conclusions than mine. He supposes a circular eddy; mine is elliptical. His centrifugal forces are equal; mine (the resultant centrifugal forces) vary harmonically. His calculation of the 'deflection to the right' is based on the assumption that the velocity around the periphery of the eddy, v in the equation $F = 2\,mv\,\Omega \sin\phi$, is a constant, whereas, in an elliptical eddy, it is an harmonic variable.

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V. L. Jones (1412 S. Norfolk, Tulsa 14, Okla.; received Oct. 31, 1955)—Anyone versed in the subject of dynamics is well aware of the fact that the phenomenon of gyroscopic action can be ascribed only to rotational motion of rigid bodies. In his 1954 paper, Cooke attempted to effect a derivation for his results from his figure. However, he fails to point out just how one would arrive at the figure he has drawn.

In the present paper Schriever has clearly demonstrated that gyroscopic action, and for that matter, the motion of rotating eddies played no part whatsoever in the formation of the Carolina Bays. Moreover, it is to be hoped that he has quieted once and for all the notion that any rotating fluid such as an eddy, a tornadic wind mass, etc., has associated with it the phenomenon of gyroscopic action.

In his Eq. (8), Schriever has shown that the decrease or increase in gravity acting on his particle of water, depending on whether it is moving east or west respectively, is 2.3 parts per 100,000. This change in weight of the particle is due solely to the vertical component of the Coriolis force by virtue of the eddy velocity v_e of four miles per hour. The total change in gravity thus experienced by the particle between the ends of a north-south diameter of Schriever's circular bay two miles in diameter at 30° N is 4.6 parts per 100,000 due to this consideration alone.

Schriever does not consider the change in weight of the particles resulting from the north-south normal change in the Earth's gravitational field strength as shown in the gravity tables computed on the International Ellipsoid. This normal change in gravity derives not only from the centrifugal effect of the rotating Earth, but also from the change which derives from the gravitational effect, due to the spheroidal shape of the Earth. Thus, instead of using 1320 ft/sec as the linear velocity V of the Earth, in the vicinity of 30° N, a more rigorous solution would require that the value of V be integrated between a maximum and minimum value at the south and north ends of a north-south diameter respectively.

For the end points of a north-south profile, two miles long at 30° N, one finds a normal change in

gravity of 2.264 mgal [*Nettleton*, 1940, p. 52]. Since the value of the gravitational field strength is approximately 980 dynes/gm, this would be a normal change in gravity (no relative velocities of the particles involved) of 0.23 parts per 100,000. When compared with Schriever's 4.6 parts per 100,000, for his particle with a velocity of four miles per hour, it is noted that the change in weight of the particle resulting from a consideration of the north-south normal change in gravity is only five per cent of his computed change. It is thus evident that a rigorous solution of the problem is unnecessary, and Schriever is quite justified in disregarding the normal change in gravity in his analysis.

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Nettleton, L. L., *Geophysical prospecting for oil*, McGraw-Hill, 1940.

William Schriever (Department of Physics, University of Oklahoma, Norman, Okla.; Author's closure)—There occur in some areas occupied by the typical Carolina Bays, depressions that very apparently have a different origin from that of the Carolina Bays.

Typical Carolina Bays are shown on mosaics made from aerial photographs of the coastal plains of North and South Carolina. These Bays even occur in southeast Virginia and in southeast Georgia. The area of occurrence is roughly 35,000 sq mi. Over this area the typical Carolina Bays are elliptical with the long axes all very approximately NW-SE. It appears that the depressions shown on Figure 3 (six by nine miles) are not of this character.

The hypothesis that the Carolina Bays were caused by solution was considered and rejected by *Melton* and *Schriever* [1933] in their first paper. Some objections to such an hypothesis are the same as those stated by Schriever in 1951 to a part of Johnson's 'Hypothesis of complex origin.' It is not at all necessary that all the depressions shown on Figure 3 must have the same origin as that of the Carolina Bays.

As I suggested [*Schriever*, 1951], it is entirely possible that the original Carolina Bay depressions were subject to deepening by solution after they were formed and had their present orientations. Any acceptable hypothesis must explain the elliptical shape and the parallel alignment over that large area of occurrence, and also why that special type of depression is not found on any other coastal plain of the Earth.

The purpose of Cooke's Professional Paper 254-I quite evidently was to arrive at the cause of the shape and the orientation of typical Carolina Bays. Cooke must have had in mind that a bay was approximately circular at the beginning for if it had been elliptical to start with, it already would have had an orientation and a shape before Cooke's eddy could have any effect, and there would be nothing to explain.

The problem of the motion of a particle of matter, such as air or water, over the surface of the spinning Earth was solved long ago. I presented a simplified derivation of the vertical and horizontal components of the well known Coriolis forces (inertial reactions). I also took into account centrifugal reaction. There is no action of the water that would make a circular eddy become elliptical. As a matter of fact if a bay had an elliptical shape, and the water were spinning, the centrifugal reaction of the water would be far greater near the ends of the minor axis than near the ends of the major axis. If such centrifugal effects were to cause erosion, the erosion would be such as to cause the elliptical bay to become a circular bay. (For a simple type of spin of the water the radius vector from the center of the elliptical bay to its periphery must sweep out equal areas in equal times. For such a spin the centrifugal reactions of a particle of water near the ends of the major and minor axes are inversely proportional to the cubes of the lengths of the axes.)

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Reviews, Abstracts, and Bibliography

Reviews and Abstracts

HERBERT RIEHL, *Tropical Meteorology*, McGraw-Hill, x + 392 pp., 1954, $8.50.

This is the first comprehensive work on tropical meteorology and is written by a meteorologist whose voluminous writings over the past decade have established him as an authority in the field.

The first four chapters deal with the elements in the tropics, wind and pressure, temperature, rainfall, and their diurnal and local variations. It is here one feels that the author makes his greatest contribution. The tireless effort and meticulous attention to detail is apparent. Obviously the author is never satisfied with theories and generalization for he will spend additional hours and days studying deviation from them.

Chapter 5 is an excellent review of recent work on convection. The reader is much impressed with the work which has gone on in this field in the last decade and which is still going on. Chapter 6 (by Raymond Wexler) is entitled The Physics of Tropical Rain. Actually it is a review of general work on cloud and precipitation physics, most of which has been done in extra-tropical latitudes. It gives a good introduction to this work. Chapter 7 covers observations and analyses in the tropics, following the methods developed under C. E. Palmer in the early 1940's. Various methods of drawing streamlines and thus representing fields of vorticity and divergence are discussed. The new student is likely to be misled about the possibility of doing this, considering the accuracy and representativeness of wind observation available.

Chapter 8, on divergence and vorticity, is perhaps an obligation expected in a text from the University of Chicago in the mid-twentieth century. Little is presented that goes beyond very elementary hydrodynamics. Its practical value, after 10-20 years of advocacy, is well summarized by the author in the final sentence of the chapter, "These deductions have not yet been properly tested by observations."

Chapters 9, 10, 11, and 12 cover the synoptic meteorology and the general circulation of the tropics. The author's tireless energy in observation is apparent again in these excellently organized chapters. One is struck by the sterility of our present day meteorological theory in some of these areas. Evidently we are going through a period when the theorists have not yet assimilated enough of the copious observational information to formulate sound working hypotheses.

A serious fault is apparent in logic beginning on page 73 where Riehl promises to discuss a method of measuring "evaporation over the ocean exactly (sic)." It turns out that this method involves formidable practical difficulties for which the author offers no solution. Somewhat later it is implied that river discharge measurements are crude, as compared with the measurements of other quantities in the hydrologic cycle. Actually river discharge is the quantity in the cycle most susceptible to precise measurement, and we know much more about river discharge than we do about evaporation.

The book fills an obvious need at the present time. Tropical meteorology is indeed fortunate to have so assiduous an observer as Riehl at this stage of its development.

CHARLES S. GILMAN

JOHN C. JOHNSON, *Physical Meteorology*, John Wiley & Sons, v + 393 pp., 1954, $7.50.

Johnson has dealt with that twilight zone where the discipline of meteorology is in transmigration with other sciences.

In this volume much of the work that has previously been scattered through publications of many sciences is brought together in a direct, concise form. It is well organized, excellently illustrated, and has a good reference bibliography at the end of each chapter.

It begins with a treatment of the effect of the atmosphere on the transmission of electromagnetic energy and systematically treats the major processes of the Earth's atmosphere.

The author had some difficulty in maintaining complete continuity between the two major aims of the book: providing a textbook at the college level where no advanced mathematics or physics is a prerequisite and at the same time providing an adequate reference book for research workers. The treatment of some topics is rather advanced for the average student, and the book is probably too comprehensive for one college course; however, it provides excellent material from which an instructor can construct a course of study.

In the attempt to keep the treatment simple, it was not always possible to be as rigorous as is desirable in research work; nevertheless, the basic laws and theories are presented with an unbiased evaluation of their strong and weak points, and the original works are cited for those requiring a more complete treatment.

HENRY F. THOMPSON

DAVID HALLIDAY, *Introductory Nuclear Physics* (second edition), John Wiley & Sons, 493 pp., 1955, $7.50.

Like the first edition of this book, this volume is a general introduction to theoretical and experimental nuclear physics, designed for use as an undergraduate or early graduate text. In this second edition more emphasis is placed on nuclear theory, thus correcting a defect of the first edition. A chapter on quantum mechanics has been added, together with appendices giving derivations of many of the important formulas as well as smaller additions to various chapters in order to bring the discussion up to date. To make room for these additions the treatment of a number of other subjects has been shortened; the geophysicist may especially miss the discussion of natural isotope abundance variations which appeared (although brief) in the first edition. The scope of nuclear physics is defined to include such subjects as the physics of fundamental particles, cosmic rays, molecular beams, and mass spectroscopy.

Writing an adequate introductory textbook on nuclear physics is in many ways an impossible task.

Whereas in other branches of physics, such as mechanics, thermodynamics, and electromagnetic theory, it is possible to give a reasonably self-consistent presentation on an elementary level, this cannot be done in nuclear physics. This arises from the fact that many of the important concepts and results of nuclear physics depend on advanced subjects such as relativistic quantum mechanics and quantum electrodynamics, thus necessitating appeals to authority at every turn. While an excellent feature of this book is the frequent use of references to the original literature, this can hardly offset the difficulty mentioned above. The student whose knowledge of quantum theory is determined by the elementary introduction in chapter two can hardly be expected to profit much from the references to theoretical articles in the *Physical Review*. On the other hand, elimination of those subjects which cannot be completely discussed in an elementary way would result in the absence of most of the important parts of nuclear physics. Thus a compromise is unavoidable, and the author has made it well. This book will prove particularly useful to the aspiring experimental physicist as well as to the ambitious nonphysicist who wishes to become familiar with nuclear physics in a rather thorough way. Although the subject of radioactive age determination is not discussed and that of isotope abundance variations barely mentioned, much of the material in this book is fundamental to an understanding of these rapidly expanding fields of geophysics. A knowledge of calculus and some familiarity with modern atomic physics should suffice as prerequisites for understanding the presentation.

A regrettable error is made on page 281 where it is stated that the theoretical curve for the Coulomb excitation yield is based on the collective model of the nucleus. This theory is given by Alder and Winther [*Phys. Rev.*, **91**, 1578, 1953] and does not make use of the collective model.

The format and illustrations are good, and many useful problems are given at the end of each chapter.

GEORGE W. WETHERILL

Bibliography

Scope of this Bibliography

This statement replaces the one published in the February 1954 issue of the *Transactions*, pages 175–76, and will serve as the guide to the selection of material for the current volume.

Emphasis in general is placed on the fundamental aspects of the several fields rather than their applications, on out-of-the-way sources likely to escape general notice, and on geophysical papers appearing in papers of broader scientific coverage. The bibliography does not include papers published in the *Transactions*, nor does it include those in any of the journals named below, except for an occasional item possessing geophysical interest beyond a certain area of specialization appropriate to the particular journal. These journals, primary source media for the various disciplines of geophysics, are readily available in schools where the Earth sciences are taught and in centers of study concerned with the respective specialties. They are here listed with key letters to show the Sections of the Union for which each one is treated as a primary source:

American Journal of Science (f, h)
American Mineralogist (f, h)
Annalen der Meteorologie (c)
Annales Biologiques du Conseil Permanent International pour l'Exploration de la Mer (e)
Archiv für Meteorologie, Geophysik, und Bioklimatologie, Ser. A, Vienna (c)
Boletin, Servicio Meteorologico Nacional (Spain) (c)
Bulletin, American Meteorological Society (c)
Bulletin d'Information du Comité Central d'Océanographie et d'Etude des Côtes (e)
Bulletin Géodésique (a)
Bulletin, Beach Erosion Board, Washington (e)
Bulletin, Geological Society of America (f, h)
Bulletin, Seismological Society of America (b)
Bulletin, World Meteorological Organization (c)
Deep-Sea Research (e)
Deutsche Hydrographische Zeitschrift (e)
Empire Survey Review (a)
Geofisica e Meteorologia (c)
Geophysical Magazine, Tokyo (c)
Geophysics (b, d)
Időjaras (Weather, Hungarian) (c)
Indian Journal of Meteorology and Geophysics (c, d)
International Hydrographic Review (e)
Journal du Conseil Permanent International pour l'Exploration de la Mer (e)
Journal of Atmospheric and Terrestrial Physics (d)
Journal of Geology (f, h)
Journal of Geophysical Research (b, d)
Journal of Marine Research (e)
Journal of Meteorological Research (c)
Journal of Meteorology (c)
Journal, Marine Biological Association of the United Kingdom (e)
Journal, Meteorological Society of Japan (c)
Journal, Oceanographic Society of Japan (e)
Journal Scientifique de la Météorologie (c)
Limnology and Oceanography (e)
Low Temperature Science, Series A, Phys-Sci. (c)
Meteorological Magazine (c)
Météorologie (c)
Meteorologische Rundschau (c)
Meteoros (c)
Monthly Weather Review, Washington (c)
Oceanographical Magazine (e)

Papers in Meteorology and Geophysics, Tokyo (c)
Papers in Physical Oceanography and Meteorology (c, e)
Proceedings, Institute of Radio Engineers, New York (d)
Quarterly Journal, Royal Meteorological Society (c)
Records of Oceanographic Works in Japan (e)
Science Reports, Tohoku University, 5th series (d)
Tellus (c, d)
Weather (c)
Weatherwise (c)
Zeitschrift für Meteorologie (c)

General—This heading includes items of broad interest in geophysics, and those of specific interest to two or more Sections, garnered in the search of the literature of particular Sections.

Geodesy (a)—Papers on theoretical geodesy and on significant geodetic operations and results are included, but not, as a rule, those on photogrammetry and cartography.

Terrestrial Magnetism and Electricity (d)—This heading covers geomagnetism, telluric and atmospheric electricity, air glow, aurora, and studies of the ionosphere and upper atmosphere as a geophysical milieu, with limited attention to collateral fields such as radio astronomy and cosmic rays; but items (from any source) that have been listed in W. E. Scott's List of Recent Publications in the *Journal of Geophysical Research* are not intentionally repeated here.

Meteorology (c)—The monthly *Meteorological Abstracts and Bibliography* largely supplies the need in this field, but some items are gleaned from the less well known foreign publications.

Oceanography (e)—All aspects of oceanography are covered except the purely biological.

Hydrology (g)—The bibliography includes much of the current literature developing hydrologic principles. It is selective only to the extent that regular serial reports on stream flow, ground water, climatology, and other basic data are excluded. Also excluded are engineering reports based on hydrologic applications, unless it is found that some new principle is set forth. It is not complete, especially in some of the peripheral aspects such as glaciology and sedimentation.

Seismology (b)—All aspects are included except applications to prospecting, but coverage is not complete. Papers that are primarily geological, or that are more properly assigned to Tectonophysics, are omitted.

Volcanology, Geochemistry, and Petrology (f)—All aspects of this broad field in so far as they relate to geophysics are covered, including heat processes and radioactivity as well as classical volcanology.

Tectonophysics (h)—All aspects of tectonophysics are covered. It is the intent to include general geologic papers having detailed discussion of structure.

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Notes and Personalia

Notes

RESEARCH POSITIONS AVAILABLE IN THE UNITED STATES INTERNATIONAL GEOPHYSICAL YEAR ANTARCTIC PROGRAM—Opportunities are open for physical scientists, engineers, and technicians in connection with the Antarctic Program now being developed by the U. S. National Committee for the International Geophysical Year. The United States program will emphasize aurora and airglow, cosmic rays, geomagnetism, glaciology, gravity, ionospheric physics, meteorology, and seismology. Major geophysical research stations will be established at Little America, Marie Byrd Land, the South Geographic Pole, on the Knox Coast, and along the Weddell Sea. Initial work on this program was undertaken a year ago by the reconnaissance voyage of the USS *Atka*. Operation Deepfreeze, currently under way, will do much of the initial work with regard to the establishment of specific stations. The scientific program will cover the period from January, 1957, to April, 1959, and scientists and technicians will leave the United States about November 1, 1956. Positions are open for the full period of investigations or for the period November, 1956 to April, 1958, and November, 1957, to April, 1959. There will be a training period of approximately two months in advance of the departure dates. There are opportunities for candidates at the bachelor's, master's, and doctorate levels of training and experience. Inquiries should be addressed to the U. S. National Committee for the International Geophysical Year, 2101 Constitution Avenue, Washington 25, D. C.

NEW SCHOOL FOR ADVANCED STUDY AT MIT—The Massachusetts Institute of Technology has recently established a new school in which postdoctoral scholars from all over the world can join with the MIT faculty on high-level theoretical studies and research. The new school will initially have the tendency to formalize the opportunities for advanced study already available at MIT. Further details may be secured by writing to the Institute in Cambridge, Massachusetts.

RESEARCH FELLOWSHIPS AND ASSISTANTSHIPS IN METEOROLOGY AND OCEANOGRAPHY AT NEW YORK UNIVERSITY—Two fellowships and a number of assistantships are available in meteorology and oceanography at New York University for the year beginning September, 1956. The first of the fellowships includes full tuition and fees and a stipend of $2500, and the second, full tuition and fees for nine months. The research assistantships are on the hourly basis. Interested persons should address the Assistant Dean in Charge of the Graduate Division, College of Engineering, New York University, New York 53, New York. Completed applications must be on file by April 1, 1956.

GENERAL ELECTRIC TEACHING FELLOWSHIPS OFFERED BY CASE INSTITUTE OF TECHNOLOGY—Fifty all-expense General Electric science fellowships to enable preparatory school and high school physics teachers from the north central states to take part in a

six-week study program to run from June 17 to July 27, 1956, are being offered by Case Institute of Applied Science in Cleveland. Applicants for the fellowships must be college graduates who possess experience in preparatory and high school teaching of science and must come from the states of Illinois, Indiana, Iowa, Kentucky, Michigan, Missouri, Minnesota, Ohio, Tennessee, West Virginia, and Wisconsin, or the western part of Pennsylvania. The fellowship includes expenses to and from Cleveland, Ohio, as well as cost of living on the Case campus, books, tuition, and fees. Further information may be secured from Elmer Hutchisson, Dean, Case Institute of Technology, 10900 Euclid Avenue, Cleveland 6, Ohio.

EARTH SATELLITE PANEL FOR THE INTERNATIONAL GEOPHYSICAL YEAR—A new Technical Panel on the Earth Satellite Program has been named by the U. S. National Committee for the International Geophysical Year, as follows: R. W. Porter (Chairman), Hugh Odishaw, Joseph Kaplan, H. E. Newell, Jr., W. H. Pickering, A. F. Spilhaus, Lyman Spitzer, Jr., J. A. Van Allen, and F. L. Whipple. The Panel will have the fundamental responsibilities for the development, coordination, and direction of the overall scientific satellite effort of the United States work in the International Geophysical Year Program.

WORK OF THE INSTITUTE OF HYDROGEOLOGY AT ISTANBUL—This Institute was established in 1952 with the aid of a UNESCO Technical Assistance Mission and has recently graduated its first class. The graduates are already at work in teams, studying the ten principal river basins of Turkey. One of the early steps in the plan is to start a systematized development of Turkey's ground-water resources.

NEW PREDOCTORAL FELLOWSHIPS OFFERED JOINTLY BY THE GEOPHYSICAL LABORATORY OF THE CARNEGIE INSTITUTION OF WASHINGTON AND JOHNS HOPKINS UNIVERSITY—Two predoctoral fellowships are offered jointly by the two organizations noted above for fellowships to extend over a two- to three-year period. The stipend for the first academic year is $2400. The first year of work is to be at the University and the second at the Geophysical Laboratory, working on a thesis problem. Applications with supporting data should be in the hands of Ernst Cloos, Geology Department, Johns Hopkins University, Baltimore 18, Maryland, by March 1, 1956.

STANOLIND FOUNDATION GRADUATE FELLOWSHIP IN GEOPHYSICS AT THE UNIVERSITY OF UTAH—A graduate fellowship carrying a stipend of $1500 plus fees and tuition has been established in geophysics by the Stanolind Foundation at the University of Utah. Further information can be secured by writing to Kenneth L. Cook, Head, Department of Geophysics, University of Utah, Salt Lake City, Utah.

CONTINUED DEVELOPMENT OF THE SEISMOLOGICAL INSTITUTE AT ISTANBUL, TURKEY—The UNESCO mission to Turkey to aid in the establishment of a Seismological Institute in Istanbul with seismograph stations at three other locations in Turkey is continuing. Takahiro Hagiwara has just returned to Japan after work in the development of the Institute. The preliminary groundwork was laid a number of years ago by Beno Gutenberg of the California Institute of Technology and was continued in subsequent years by F. J. Roesli of Switzerland and Gaston Grenet of France.

ERUPTION OF LONG-INACTIVE VOLCANO—Volcano Bezymyanny on the Kamchatka peninsula, considered extinct for hundreds of years, erupted on October 20, 1955, it is reported by the Volcanological Laboratory of the Soviet Academy of Sciences. The cloud of ashes, fumes, and vapor swelled to a height of six miles in mid-November.

NEW STORM-SURGE INVESTIGATION UNDER WAY AT LAMONT GEOLOGICAL OBSERVATORY—A study to investigate the causes and possible means of forecasting such storm surges as that which occurred in Lake Michigan in June, 1954, and at Staten Island in November, 1953, is now being conducted by the staff of the Lamont Geological Observatory of Columbia University under the direction of Maurice Ewing. The work is being sponsored by the American Institute of Mining and Metallurgical Engineers under a grant from the Engineering Foundation.

Personalia

LEROY R. ALLDREDGE, Secretary, Section of Terrestrial Magnetism and Electricity, and formerly Chief of the Electricity and Magnetism Research Division of the National Ordnance Laboratory, has resigned to accept the position as Operations Analyst of the Operations Research Office, Johns Hopkins University.

HARVEY O. BANKS has been named State Engineer of California to succeed A. D. Edmonston, who has retired.

LLOYD V. BERKNER, President of Associated Universities Incorporated, has been appointed a Rear Admiral in the United States Naval Reserve.

JOSEPH C. BOYCE, Associate Director of the Argonne National Laboratory, has been named Vice President of Academic Affairs and Dean of the Graduate School at Illinois Institute of Technology.

DETLEV W. BRONK, President of the National Academy of Sciences, and President of the Rockefeller Institute for Medical Research, has been elected the Chairman of the National Science Board.

JOHN S. BURLEW has been named Director of the Franklin Institute in Philadelphia. He joined the Institute in 1954, up to which time he had been the Technical Director of the Cambridge Corporation.

A. D. EDMONSTON, State Engineer of California, retired November 1, 1955, after more than 31 years of service with the State. He was named State Engineer in 1950 to succeed the late Edward Hyatt.

GEORGE GAMOW, Professor of Theoretical Physics at George Washington University, has been granted leave of absence for the spring semester to work with the Convair Company in San Diego, California, on problems relating to the International Geophysical Year.

JOHN C. REED, of the U. S. Geological Survey, has accepted designation as Chairman of the Research Committee of the Arctic Institute of North America.

THORNDIKE SAVILLE, Dean of Engineering at New York University, has recently been elected President of the Engineers Council for Professional Development.

ATHELSTAN SPILHAUS, Dean of the Institute of Technology at the University of Minnesota, and member of the Executive Board of UNESCO, presented the views of the United States on the problems of UNESCO before the Board at its 42nd session in Paris in November. He also addressed the meeting of the U. S. National Commission on UNESCO which met in Cincinnati in early November.

ARTHUR D. BUTTERFIELD died August 22, 1955, at the age of 84. He was born at Dunstable, Massachusetts, and took his baccalaureate degree from Worcester Polytechnic Institute in 1893, and his master's degree in 1898. He received a master's degree from Columbia University in 1904, and in 1945 he was given an honorary doctorate by Worcester Polytechnic Institute. He began his professional career by the teaching of mathematics and geodesy at the University of Vermont in 1898 and continued his active work at the University until 1944, at which time he became Director of the Department of Land Records of the State of Vermont. He had been a member of AGU since 1934.

WILLIAM GRANT, Consulting Engineer of Fort Worth, Texas, died October 14, 1955, at the age of 83. After taking his baccalaureate degree in civil engineering at the University of Nebraska in 1897, he began his professional work as a locating and bridge engineer for the Chicago, Burlington, and Quincy Railroad, where he continued until 1906. From 1906 to 1909 he served as City Engineer for the City of Lincoln, Nebraska, and in 1909 he opened his own office as a consulting engineer. In recent years he has been associated with Freese and Nichols, Consulting Engineers of Fort Worth. He had been a member of AGU since 1934.

ROY WALDO MINER, Curator Emeritus of Marine Life of the American Museum of Natural History in New York, died December 13, 1955, at the age of 80. He was born in North Adams, Massachusetts, and took his baccalaureate degree from Williams College in 1897 and was awarded a Doctor of Science degree in 1927. He took his doctorate from Columbia in 1923. His early career was devoted to teaching in high schools and preparatory schools, but in 1905 he began his services with the American Museum of Natural History as Assistant Curator of Invertebrate Zoology and became Curator of Marine Life in 1922. He engaged in a number of scientific expeditions, chiefly in the Caribbean and South Pacific regions. He had been a member of AGU since 1942.

ROBERT K. SOUTER, Test Engineer of the Army Chemical Center near Bel Air, Maryland, died November 18, 1955, at the age of 39. He was born at Scranton, Pennsylvania, and took his baccalaureate degree from Rensselaer Polytechnic Institute in 1938. He first served Pan American Airways as an airline meteorologist and subsequently became an instructor in meteorology and navigation at the Heald Engineering College in San Francisco. From 1940 to 1944, he served the National Advisory Committee for Aeronautics as Research Engineer at Langley Field, Virginia, continuing with the Committee in other capacities until 1951. At that time he entered the service of the Technical Air Command of the United States Air Force, which service continued until 1953, when he entered on his duties as Test Engineer for the Army Chemical Center. He had been a member of AGU since 1947.

HENRY C. STETSON, Submarine Geologist and Oceanographer of the Museum of Comparative Zoology of Harvard University, died aboard the *Atlantis* off the west coast of South America on December 3, 1955, at the age of 55. He was born in Cambridge, Massachusetts, took his baccalaureate degree from Harvard in 1923, and his master's degree in 1925, and had devoted his entire professional career to work associated with Harvard University as Assistant Curator, Research Associate, Research Fellow, and Research Oceanographer. During the war years he was associated with the Office of Scientific Research and Development and served in the Navy. He had been a member of AGU since 1937.

Union, Section, and Committee Activities

Proposed Change in Name of Section of Terrestrial Magnetism and Electricity

A Committee was appointed by the President of the Section of Terrestrial Magnetism and Electricity to consider other names for the Section and to make recommendations. The report of the Committee is as follows:

The Committee appointed to recommend a name for the Section of Terrestrial Magnetism and Electricity has unanimously agreed to recommend the name Section of Geomagnetism and Upper Atmosphere.

E. O. HULBURT, *Chairman*
N. C. GERSON
ROSS GUNN
DAVID G. KNAPP

The Executive Committee of the Section thanks the above Committee for its work and feels that definite action should now be taken in this matter by the Section so that a formal recommendation can be made to the Executive Committee of the Union. To help determine the consensus of Section members it is requested that they write to the Section Secretary expressing their choice of a name from the list below.

(1) Section of Geomagnetism and Upper Atmosphere (recommendation as above)
(2) Section of Terrestrial Magnetism and Electricity (present Section name)
(3) Section of Geomagnetism and Aeronomy (name of International Association of which we are the U. S. group)
(4) Section of _____ (write in other choice)

If sufficient response is received from this notice, the results will be used as the basis for a recommendation to the Executive Committee of the Union. If the response is not adequate, action will be taken at the Thirty-Seventh Annual Meeting to be held April 30 to May 2, 1956 in Washington.

LEROY R. ALLDREDGE, *Secretary*
3133 Jennings Road,
Kensington, Maryland

Permanent Research Committees of Section of Hydrology as of January 1, 1956

(Note: Chairmen were appointed for the triennium ending June 30, 1958. Terms of appointment of members expire on June 30 of the year indicated.)

Chemistry of Natural Waters: L. D. DONEEN (*Chairman*), LYMAN R. FLOOK, JR. (1956), RAYMOND A. HILL (1956), NORRIS W. RAKESTRAW (1956), HARVEY O. BANKS (1957), ARNO T. LENZ (1957), I. W. WALLING (1957), L. O. FINE (1958), MILTON FIREMAN (1958), WILLIAM B. PETERS (1958)

Dynamics of Streams: D. C. BONDURANT (*Chairman*), MAURICE L. ALBERTSON (1956), ALVIN G. ANDERSON (1956), M. R. CARSTENS (1956), WHITNEY M. BORLAND (1957), NORMAN H. BROOKS (1957), ARTHUR T. IPPEN (1957), no appointments made for 1958

Evaporation and Transpiration: MARVIN D. HOOVER (*Chairman*), R. W. GERDEL (1956), J. KITTREDGE (1956), C. H. M. VAN BAVEL (1956), G. EARL HARBECK, JR. (1957), RAY K. LINSLEY (1957), HOWARD W. LULL (1957), E. A. COLMAN (1958), WALTER GARSTKA (1958), THOMAS ROBINSON (1958)

Glaciers: ARTHUR JOHNSON (*Chairman*), TROY L. PEWE (1956), ROBERT P. SHARP (1956), FRED M. VEATCH (1956), RALPH MASON (1957), MARK F. MEIER (1957), M. E. BEATTY (1958), OLIVER KEHRLEIN (1958), SVENN ORVIG (1958)

Ground Water: JOHN C. FRYE (*Chairman*), HARVEY O. BANKS (1956), H. H. COOPER, JR. (1956), FRANK C. FOLEY (1956), J. C. CALHOUN (1957), W. J. DRESCHER (1957), M. KING HUBBERT (1957), JOHN F. MANN (1958), GEORGE B. MAXEY (1958), HAROLD E. THOMAS (1958)

Infiltration: LEONARD SCHIFF (*Chairman*), HOWARD L. COOK (1956), HOWARD W. LULL (1956), DONALD E. WHELAN (1956), VLADIMIR S. ARONOVICI (1957), JAMES H. BROWN (1957), GEORGE R. TRIMBLE (1957), ELDRED BLISS (1958), IRWIN REMSON (1958), MAX SUTER (1958)

Lakes: ERNEST F. BRATER (*Chairman*), NORMAN BILLINGS (1956), W. C. KRUMBEIN (1956), JAMES H. ZUMBERGE (1956), JAY V. HALL, JR. (1957), G. WILLIAM HOLMES (1957), JAMES L. VERBER (1957), WALLIS S. HAMILTON (1958), WILLIAM T. LAIDLY (1958), C. O. WISLER (1958)

Land Erosion: L. C. GOTTSCHALK (*Chairman*), HENRY W. ANDERSON (1956), J. B. STALL (1956), ARTHUR N. STRAHLER (1956), G. ROBERT HALL (1957), FINLEY B. LAVERTY (1957), ROBERT V. RUHE (1957), PAUL C. BENEDICT (1958), JOHN E. KESSERLI (1958), LUNA B. LEOPOLD (1958)

Physics of Soil Moisture: ROBERT D. MILLER (*Chairman*), PAUL R. DAY (1956), ARNOLD KLUTE (1956), JAMES N. LUTHIN (1956), WALTER H. GARDNER (1957), STERLING A. TAYLOR (1957), G. H. BOLT (1958), C. B. TANNER (1958)

Precipitation: WILLIAM E. HIATT (*Chairman*), AUSTIN E. HELMERS (1956), ELMO W. MCCLENDON (1956), A. L. SHANDS (1956), H. ALDEN FOSTER (1957), ARCHIE M. KAHAN (1957), C. C. MCDONALD (1957), FLOYD HUFF (1958), H. C. S. THOM (1958), DAVID K. TODD (1958)

Runoff: VEN TE CHOW (*Chairman*), BERTRAM S. BARNES (1956), ANTHONY POLIS (1956), W. D. POTTER (1956), GORDON AYER (1957), HAROLD W. HOBBS (1957), GEORGE R. SHANKLIN (1957), ALFRED J. COOPER (1958), NEAL E. MINSHALL (1958), HAROLD E. THOMAS (1958)

Snow: R. A. WORK (*Chairman*), GORDON KIDD (1956), VINCENT SCHAEFER (1956), ROBERT D. ELLIOTT (1957), J. VAN DE ERVE (1957), CALVIN C. WARNICK (1957), DEAN BOGART (1958), WALTER E. JOHNSTON (1958), M. W. NELSON (1958)

Pacific Northwest meeting held in Portland, November 17–18, 1955

A Pacific Northwest Regional meeting was held in Portland, November 17 and 18, 1955. The official registration was 76, despite the bad weather conditions prevailing prior to and during the meeting. Those in attendance came from Oregon, Washington, Idaho, California, British Columbia, and the District of Columbia. A business meeting was held November 17, at which it was decided to hold the 1956 meeting in the Seattle-Tacoma area.

Nine papers were presented at the technological sessions. The luncheon meeting was addressed by William A. Pearl, Administrator of the Bonneville Power Administration, and following a dinner meeting, L. H. Foote, Brigadier General of the North Pacific Division of the Corps of Engineers, addressed the group on the current activities in the Corps.

VAIL P. SCHERMERHORN
Secretary-Treasurer

Additions to the Membership

May 10, 1955 to January 10, 1956

ALEXANDER, LCDR. ROBERT J., 69 Selby Blvd., Worthington, Ohio (*ae*)

ALLEN, MR. DOUGLAS W., 42 Glendonwynne Rd., Toronto 9, Ont., Canada (*fh*)

ATEN, MR. RICHARD EUGENE, P. O. Box 232, Urbana, Ill. (*g*)

BAKER, MAJ. RAY GORDON, 631 Galveston Pl., S. E., Washington, D. C. (*b*)

BARTLETT, MR. ALEXANDER G., 80 Maywood Dr., San Francisco 27, Calif. (*eg*)

BISSELL, MR. LENARD M., 8917 Boulder Ave., Vancouver, Wash. (*c*)

BLANCHARD, MR. FRANCIS B., 2945 Linden Ave., Berkeley 5, Calif. (*g*)

BONIWELL, MR. JOHN BEWERS, Rio Canadian Exploration, Ltd., 220 Bay St., Toronto, Ont., Canada (*bdfg*)

BOUCOT, MR. ARTHUR J., 5314 Eighth Road, S., Arlington, Va. (*h*)

BROWN, MR. RALPH S., 5749 Eberle St., Long Beach 11, Calif. (*fg*)

BROWN, MR. RODGER A., 27 Eckerson Ave., Akron, N. Y. (*c*)

BUTLER, MR. DONAL A., 1818 S. Keeler St., Bartlesville, Okla. (*abcdefgh*)

CADAVID CARDONA, SR. HERNANDO, Apartado Nacional 2321, Medellin, Colombia (*cg*)

CARVER, DR. CHARLES E., JR., Hydrodynamics Section, Mail No. 370-B, The Glenn L. Martin Co., Baltimore 3, Md. (*ceg*)

CHEPIL, DR. W. S., Agronomy Dept., Kansas State College, Manhattan, Kans. (*cg*)

CHEW, MR. FRANK, Marine Lab., University of Miami, Coral Gables, Fla. (*ce*)

CLARK, MR. JOHN F., Naval Research Lab., Code 7120, Washington 25, D. C. (*d*)

CLIFFORD, MR. EDWARD LEHR, 3618 Idaho St., Houston 21, Texas (*b*)

COOK, PROF. WILLIAM H., Loyola University, 7101 W. 80th St., Los Angeles 45, Calif. (*abgh*)

COOPER, MR. ALFRED J., TVA, 702 Union Bldg., Knoxville, Tenn. (*cg*)

CORCORAN, MR. ROBERT H., Soil Conservation Service, P. O. Box 1438, Huron, S. Dak. (*g*)

CRAIG, MR. ROBERT N., 7809 Dartmoor Dr., Normandy 21, Mo. (*cg*)

CRAWFORD, MR. TODD VINCENT, 146½ S. Doheny Dr., Beverly Hills, Calif. (*cg*)

CRONE, MR. JOHN L., 3522 Nimitz Rd., Kensington, Md. (*cd*)

CROWE, MR. CHRISTOPHER, Dept. of Physics, University of Western Ontario, London, Ont., Canada (*bdh*)

CUMMING, DR. GEORGE LESLIE, Canadian Gulf Oil, P. O. Box 130, Calgary, Alta., Canada (*bfh*)

CUNNINGHAM, DR. ROBERT MORTON, Box 108C, R.F.D. 1, Concord, Mass., (*c*)

CURRY, MR. R. BRUCE, Agr. Eng. Dept., University of Missouri, Columbia, Mo. (*cg*)

DAVIDSON, MR. ALEXANDER L. C., % Bank of N. S. W., 29 Threadneedle St., London, EC 2, England (*bg*)

DIETERICH, MR. JOHN HARVEY, 1949 Wylie St., Missoula, Mont., (*abcdefg*)

DOE, MR. L. A. EARLSTON, Creole Petroleum Corp., Apdo. 172, Maracaibo, Venezuela (*ceg*)

DOELL, DR. RICHARD RAYMAN, 46 Saranac Blvd., Toronto, Ont., Canada (*d*)

DUNN, MR. ALLISON VAN VLIET, 3215 Newark St., N. W., Washington 8, D. C. (*g*)

EAGLESON, PROF. PETER S., Room 48–102, Massachusetts Institute of Technology, Cambridge 39, Mass. (*eg*)

EDINGER, MR. JAMES G., 1433 Tigertail Rd., Los Angeles 49, Calif. (*c*)

ELEVATORSKI, MR. EDWARD A., 2110 New York St., S. W., Albuquerque, N. Mex. (*g*)

ELLIS, MR. ROY, Centre College, Danville, Ky. (*ce*)

ESCHMAN, DR. DONALD FRAZIER, Dept. of Geology, University of Michigan, Ann Arbor, Mich. (*befgh*)

EVERSON, MAJ. CLARENCE E., AO-873212, 1st Weather Wing, APO 925, % PM, San Francisco, Calif. (*c*)

EWING, COL. CLAIR EUGENE, AF Missile Test Center, Patrick AFB, Cocoa, Fla. (*ac*)

FALCONE, MR. ZELWOOD W., Texas A & M Research Foundation, Faculty Exchange 44, College Station, Tex. (*eg*)

FINE, DR. LAWRENCE OLIVER, 1042 Seventh Ave., Brookings, S. Dak. (*g*)

FINNEGAN, CAPT. HENRY E., 1605 35th St., N. W., Washington 7, D. C. (*e*)

FIREMAN, DR. MILTON, Agr. Extension Service, University of California, Riverside, Calif. (*g*)

DA FONSECA OLIVEIRA, DR. JOSE TIAGO, Faculdado de Ciencias de Lisbon, Lisbon, Portugal (*abg*)

FOOTE, MR. ROYAL S., 3321 Madison St., Denver, Colo. (*d*)

FOURNIER D'ALBE, DR. EDWARD M., Calle Fresnos 53, Mexico City 20, D. F., Mexico (*ceg*)

FRISCHE, MR. RICHARD H., P. O. Box 285, Campus Sta., Socorro, N. Mex. (*abcdfgh*)

FUQUA, MRS. IRENE S., 3411 Granada St., Dallas 5, Tex. (*aefh*)

GALE, MR. LOUIS A., 224 Allison Ave., Ottawa 3, Ont., Canada (*a*)

GAST, MR. JAMES AVERY, Dept. of Oceanography, University of Washington, Seattle, Wash. (*e*)

GELLER, MR. ROMAN F., JR., Inter Amer. Geodetic Survey, Ft. Clayton, Canal Zone (*ad*)

GLOVER, MR. ROBERT ELLSWORTH, 1936 S. Lincoln St., Denver, Colo. (*bg*)

GOLDICH, PROF. SAMUEL S., Dept. of Geology, University of Minnesota, Minneapolis 14, Minn. (*f*)

GOODRIDGE, MR. JAMES D., 7430 Antelope Rd., Citrus Heights, Calif. (*gc*)

GRANT, MR. LEWIS O., 765 Revere St., Denver 8, Colo. (*c*)

GRETENER, DR. PETER EDWARD, 1215 18th Ave., N. W., Calgary, Alta. Canada (*bdefgh*)

GRIFFIN, MR. WILLIAM C., 1021 N. L St., Tacoma, Wash., (*cg*)

GUNNERSON, MR. CHARLES GILBERT, 6843 Vanport Ave., Whittier, Calif. (*eg*)

HAFSTAD, DR. L. R., Research Lab. Div., General Motors Corp., P. O. Box 188, No. End Sta., Detroit 2, Mich. (*d*)

HAHN, MR. CHARLES L., 78 Wayne St., Hilliards, Ohio (*g*)

HARPER, MR. ZANE R., 1517 N. E. 12th Ave., Portland 12, Ore. (*g*)

HARRIS, MR. D. LEE, U. S. Weather Bureau, 24th and M. St., N. W., Washington 25, D. C. (*ced*)

HAWES, MR. CHARLES G., Spriggsmoor S. Brent, Devon, England (*g*)

HAYMES, MR. ROBERT C., Dept. of Physics, New York University, University Heights, New York 53, N. Y. (*d*)

HEALY, MR. HENRY G., 222 E. 51st St., New York 22, N. Y. (*g*)

HIGGS, MR. DONALD V., 3737 Bellaire Blvd., Houston, Texas (*fh*)

HITSCHFELD, DR. WALTER, Physics Dept., McGill University, Montreal 2, Que., Canada (*c*)

HORTON, MR. JEROME S., 123 Skyline Dr., Vicksburg, Miss. (*g*)

HOUGH, MR. WILLIAM S., Natl. Bureau of Standards, Central Radio Propagation Lab., Boulder, Colo. (*dg*)

JACOBS, DR. JOHN ARTHUR, Geophysical Lab., University of Toronto, Toronto, Ont., Canada (*df*)

KAPLAN, MR. HENRY G., 12 Crabtree Lane, Levittown, N. Y. (*c*)

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KOLOSEUS, MR. HERMAN JOHN, 211 Finkbine Park, Iowa City, Iowa (*ceg*)

KRAMER, MR. GEORGE E., JR., P. O. Box 6557, Houston, Tex. (*b*)

KUELLMER, DR. FREDERICK J., State Bureau of Mines and Mineral Resources, Socorro, N. M. (*fh*)

LANGLEBEN, DR. M. PHILLIP, Dept. of Physics, McGill University, Montreal 2, Que., Canada (*cd*)

LITTLEWOOD, MR. WILLIAM H., 314 Poplar St., Wyandotte, Mich. (*e*)

LODGE, DR. JAMES P., JR., Robert A. Taft San. Engr. Cent., 4676 Columbia Pkway., Cincinnati, Ohio (*c*)

LOVEJOY, MR. EARL M. P., 800 Airport Rd., Reno, Nev. (*bdfgh*)

LUFBURROW, MR. ROBERT A., P. O. Box 258, Woods Hole, Mass. (*e*)

MACK, MR. SEYMOUR, Apt. 29, 2921 Calderwood Lane, Sacramento, Calif. (*cfg*)

MALONE, DR. THOMAS F., 319 N. Quaker Lane, West Hartford 7, Conn. (*c*)

MANGE, DR. PHILLIP W., CSAGI Secretariat, Service du Rayonnement, I.R.M., 3 Avenue Circulaire, Uccle, Belgium (*d*)

MANNES, MR. W. H., 1502 Milford St., Houston, Tex. (*bdg*)

MATSUSHITA, DR. SADAMI, Geophysical Institute, Kyoto University, Kyoto, Japan (*cdf*)

MAXEY, MR. GEORGE G., State Geological Survey, Urbana, Ill. (*g*)

MCCLINTOCK, MR. FRANKLIN T., Solebury, Bucks County, Pa. (*cde*)

MCHUGHS, MR. JAMES H., 5909 "A" St., Little Rock, Ark. (*cg*)

MIRANDA, MR. HENRY A., JR., 53 Circuit Ave., Tuckahoe, N. Y. (*d*)

MITCHELL, MR. JOHN T., JR., 1429 Stainback Ave., Nashville 7, Tenn. (*g*)

MOORE, MR. CHARLES B., 7 Quincy Ave., Lexington 73, Mass. (*dc*)

MORRISSEY, MR. KENNETH B., P. O. Box 1318, Port-au-Prince, Haiti (*cg*)

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Special Announcements

THIRTY-SEVENTH ANNUAL MEETING, WASHINGTON, D. C., APRIL 30 TO MAY 2, 1956, WITH SYMPOSIUM ON THE ANTARCTIC, APRIL 26–27, AND MEETINGS IN METEOROLOGY EXTENDING TO MAY 4—Attention is called to previous announcements regarding this meeting that have been published in the *Transactions*, especially that in October, 1955, pages 935–936, relating particularly to program matters, and that in December, 1955, page 1121, bringing the program matters up to date and giving information on the block booking of hotel rooms. Program details are rapidly being settled, and some Sections have their programs largely formulated. The programs close officially on March 5, 1956, in most cases, but, as noted in the December announcement, the closing date for certain portions was February 1. Three copies of the titles and abstracts should be in at the latest by March 5, 1956, with word concerning the amount of time desired (10 to 20 minutes to be allowed) and projection equipment needed. Filled programs will be closed in advance of March 5.

SUGGESTED NAME CHANGE FOR SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY—Attention is called to the report of the Section of Terrestrial Magnetism and Electricity under the heading of Union, Section, and Committee Activities regarding suggested changes in the name of the Section. All those interested in the work of this Section should give this matter their serious consideration and write to the Secretary of the Section, Leroy R. Alldredge.

ELECTIONS IN 1956—The list of official nominees for officers of the Union and of the Sections and of three of the Regional Committees for the triennium July 1, 1956 to June 30, 1959 was published in the December, 1955, issue of the *Transactions*, pages 1119–1120, to-

gether with the time schedule of election procedure. About March 1 ballots will be mailed to all members, which will convey the names of official and petition nominees, together with brief biographical sketches of each nominee. Balloting will close on March 31. Be on the lookout for a ballot.

Also included will be a ballot relating to a change in Article 3(a) of the Statutes that has been approved by the Executive Committee [see December issue, p. 1113].

ELEVENTH GENERAL ASSEMBLY OF THE IUGG—Plans were initially laid at the Tenth General Assembly of the International Union of Geodesy and Geophysics in Rome in 1954 to hold the Eleventh General Assembly in Argentina in 1957. This arrangement has now been cancelled, and it appears increasingly likely that the Eleventh General Assembly will be held in late July and early August, 1957, in Toronto, Canada. Watch SPECIAL ANNOUNCEMENTS for further word with regard to this.

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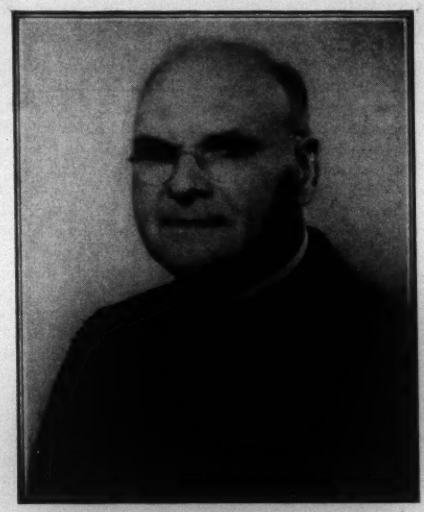
American Geophysical Union

VOLUME 37 APRIL 1956 NUMBER 2

James Bernard Macelwane, S.J.

James Bernard Macelwane, S.J., was born on September 28, 1883, on the northern shore of Sandusky Bay near Port Clinton, Ohio. He was the second oldest of nine children, five boys and four girls. He received his early education at a public school about a mile and one-half from his home. From 1901–1903 he attended the high school of Saint John's College in Toledo, Ohio. On August 31, 1903, he joined the Jesuit Order.

After two years of study and ascetical life as a novice, he took the religious vows as a Jesuit on September 8, 1905. Thereafter he followed the course of studies required of Jesuits who are being trained for the priesthood. Except for some years of teaching, he gave his attention to ancient and modern languages, literature, and history, to the natural sciences and mathematics, to philosophy and psychology, and to dogmatic, moral, and ascetical theology. These years of study culminated in ordination to the Catholic priesthood in 1918.



JAMES BERNARD MACELWANE
President, American Geophysical Union, 1953–1956

Father Macelwane's early preferences in the matter of specialized study lay in the field of classical languages, and he took his M.A. degree

in 1911. He had shown a marked talent in scientific studies. Hence, at the bidding of his religious superiors, he then pursued courses in physics and mathematics, taking an M.S. degree in 1912. Because his first formal studies in physics were pursued at Saint Louis University where a seismograph was installed in 1909, he became interested in the theory of the seismograph. He was coauthor of an article entitled "Physics of the Seismograph." This was his first technical paper; it was published in 1911.

In 1921 he took up study for the doctorate in physics, seismology, and mathematics at the University of California in Berkeley. After taking the Ph.D. in 1923, he stayed for two more years at the University of California as an Assistant Professor of Geology. During these two years he organized graduate study in geophysics and had charge of the seismographic stations of the University at Berkeley and at Lick Observatory on Mount Wilson. In 1925 he was appointed Professor of Geophysics and Director of the new Department of Geophysics in Saint Louis University, a position he held until his death.

Father Macelwane's many years at Saint Louis University will be remembered by reason of his important academic developments and services. In addition to his research in geophysics which he carried on continuously, he left a deep organizational and scholarly imprint on the University's Graduate School of which he was Dean from 1927 to 1933. In the fall of 1944 he established and was the first Dean of the Institute of Technology, the University's School of Earth Sciences and Engineering. Although he served on many University committees, was a member of the Board of Trustees, and was engaged in numerous extra-University labors in addition to his normal administrative duties, he always managed to teach at least one, and usually two, courses up until the time he was hospitalized in November, 1955. He wrote several books, and 133 technical papers of his appeared in various learned journals.

Because of his broad and sympathetic interests, his services were in constant demand. In 1947 he was appointed to the Research and Development Board of the Department of Defense. Two years later he became a member of the Scientific Advisory Board of the USAF. In 1952 he was appointed a member of the Committee on Institutional Research Policy of the American Council on Education. A presidential appointment made him a member of the National Science Board of the National Science Foundation in 1954. More recently he was appointed Chairman of the United States Technical Panel on Seismology and Gravity for the International Geophysical Year of 1957–1958.

He was a member of over two dozen learned and professional societies, in many of which he was chosen by his colleagues to serve in various official capacities. In 1926 he became a member of the American Geophysical Union. His membership was of an active character. He was Vice Chairman of the Section of Seismology, 1935–1938; President of the Section, 1938–1941; a member of the Executive Committee in 1947. In 1953 he was elected President of AGU; he was in his third year of this office when he died.

Through his effective leadership the Jesuit Seismological Association was organized in 1925. He was annually elected President of it until his death. The Eastern Section of the Seismological Society of America was also formed in 1925, and Father Macelwane's name is numbered among those who were instrumental in its establishment.

Many honors came to him. In 1948 the AGU William Bowie Medal was bestowed on him. He received four honorary degrees, was made an Honorary Life Member of the Society of Exploration Geophysicists, received the Villanova University Mendel Medal, and was given the AIME Jackling Lecture Award. He was a Fellow in a number of learned societies and a member of the National Academy of Sciences.

Undoubtedly, one of Father Macelwane's favored diversions from his many labors was to engage in field geology. He personally conducted a number of geology camps for students in the foothills of the Colorado Rockies in the vicinity of Canon City. Those who participated in these geological expeditions will remember him as a delightful companion and as a man of untiring zeal in searching out the Earth's history as revealed in its exposed rocks.

Because of general fatigue and intestinal disturbances he was hospitalized on November 21, 1955. An exploratory operation on December 19 revealed acute necrosis of the liver and later evidence also showed serious impairment of the kidneys. Although he suffered little pain in his last weeks of illness, he impressed all by the great patience with which he conducted himself during the many weeks of hospital inconveniences. He died peacefully at 7:40 a.m., February 15, 1956. He is survived by three brothers and three sisters, John Patrick, Alexander Patrick, Arthur Aloysius, Sister Mary Perpetua, O.S.U., Mother John Baptist, O.S.U., and Mary Helen Macelwane.

Victor J. Blum, S.J.

The Spectrum of the Variation in Latitude

PHILIP RUDNICK

(Contribution from Scripps Institution of Oceanography, University of California, New Series, No. 848)

Abstract—A Fourier series analysis of the motion of the Earth's rotation axis in the frequency range 0.74 to 1.14 cycles per year, containing 93 pct of the total power in the motion, shows: (1) an annual line without recognizable structure comprising about 22 pct of the power in the region examined; (2) the Chandler component comprising about 78 pct of the power, with band structure somewhat broader than heretofore recognized, leading to a value 9.5 yr for the amplitude decay time; (3) an annual component of excitation in agreement with previous determinations, equivalent to a root-mean-square displacement of the axis of inertial symmetry of 0.023″ of arc; (4) a continuous spectrum of excitation which is well determined in the Chandler region, at least roughly determined at other frequencies below annual, but not determined above the annual frequency. The magnitude of the continuous spectrum below annual frequency is consistent with the hypothesis that it, in association with the annual line, arises in the atmosphere, but lack of a determined spectrum at higher frequencies prevents examination of side-band symmetry.

Introduction—Variation of latitude arises from a motion of the pole of instantaneous rotation of the Earth, with respect to the Earth itself [*Jeffreys*, 1952, Chap. 7]. The motion has a west-to-east rotatory character, with a root-mean-square radius of 0.16 seconds of arc or 16 feet on the Earth's surface. Frequency analysis of the motion shows two main components, an annual term with frequency one cycle per year, and the Chandler component of lower frequency, about $\frac{7}{6}$ cycle per year. This spectrum has received considerable study, notably by *Pollak* [1927], and *Jeffreys* [1940]; an additional study, somewhat more elaborate than any preceding, is reported here.

The Chandler frequency is recognized to be that of a free motion of the rotating Earth, considered as a rather highly resonant mechanical filter whose statistically steady output is the observed motion of the pole of rotation. There must be a corresponding steady input to sustain the motion.

One mechanism of excitation is easy to visualize. The free motion of the rotation axis is a contracting spiral whose center is the inertial symmetry axis. If redistribution of mass anywhere in or on the Earth changes the position of the symmetry axis, the rotation axis will begin a new spiral motion about the new center. Thus position of the inertial axis may be considered the input to (or excitation for) the mechanical filter, and the position of the rotation axis its output. Input and output are like quantities, both being angular orientations. *Munk* and *Groves* [1952] have shown that the output may be excited by several possible mechanisms, but that the combined effect of these can be represented as an equivalent motion of the inertial axis. Such a representation will be assumed throughout this discussion.

Figure 1 shows the qualitative forms to be expected for the power spectra of input and output, and the spectral transmission of the mechanical filter. The prominence of the Chandler frequency in the output is ascribed entirely to the selective action of the filter, responding to random excitation. The input spectrum at this frequency need not, of course, be flat as shown, but no special feature is expected at the Chandler frequency. The annual term in the output, on the other hand, is ascribed entirely to a corresponding term in the input, no special behavior of the filter being expected at this frequency. Thus three successive objectives may be listed for study of the output spectrum.

(a) Near the Chandler frequency, the output spectrum gives the form of the filter resonance curve. Mechanical theory then permits extrapolation of this curve to obtain the filter response at all other frequencies. These results are used in the subsequent steps.

(b) Near the annual frequency, any structure discerned in the output spectrum also applies to the input spectrum and hence may contribute to understanding of the mechanism of excitation for the annual component.

(c) Measurement of the output spectrum at points sufficiently separated from both Chandler and annual frequencies may give information on the continuous component of excitation (part of which is responsible for the Chandler component of output) about which very little is known.

The present work was undertaken with primary

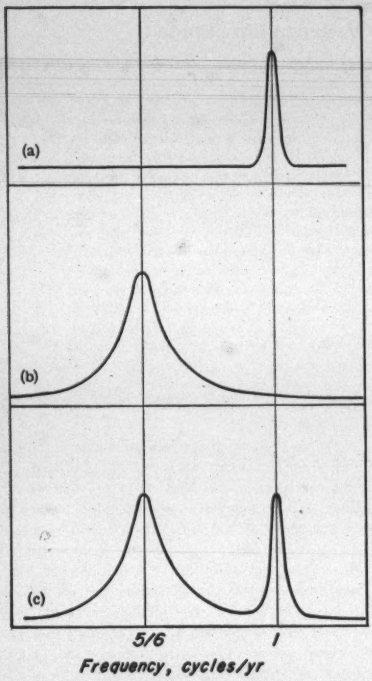


FIG. 1 – Polar motion, expected forms of spectra; (a) power spectrum of input, motion of pole of inertia; (b) spectral transmission of mechanical filter, the rotating earth; (c) power spectrum of output, motion of pole of rotation; this curve is the product of the upper two.

attention on (c), but only a little progress was found possible with presently available data. Some new information under (a) and (b) has been produced, however, and is the chief content of this report.

Notation and mathematical relations—Since the free motion of the rotation axis is a damped circular one, it is very convenient to express the spectrum analysis in terms of circular components, which in turn are conveniently described by complex exponential functions. In this system positive and negative frequencies must be distinguished, as they refer to opposite senses of rotation. This approach is embodied in the following definitions and relations.

l, m direction cosines of the Earth's rotation axis, in respective azimuths 0° and 90° E. longitude. 0.01″ of arc (or very closely one foot arc length on the Earth's surface) is the unit of measure used throughout.

$n = l + im$ a single complex number giving the position of the rotation axis in two dimensions. It obeys the differential equation

$$dn/dt = i\gamma(n - n_0) \qquad (1)$$

n_0 the time-dependent complex quantity representing excitation. It may represent position of the inertial axis, or the more general quantity $[\lambda_i + \lambda_v + \lambda_a + i(\mu_i + \mu_v + \mu_a)]$ of *Munk* and *Groves* [1952]. Unit of measure is 0.01″ of arc.

t time in years.

$\gamma = \omega_0 + i\alpha$ a complex constant, with ω_0 and α real and positive, such that

$$n = e^{i\gamma t} \qquad (2)$$

is a free motion of the rotation axis, possible when $n_0 = 0$.

ω_0 the mid-band radian frequency, per year, of the Chandler component of motion.

$1/\alpha$ the time for e^{-1} amplitude decay of the free motion (2), in years.

ω an arbitrary radian frequency, per year, either positive or negative.

The spectral transmission of a filter described by (1) is derived by supposing steady single-frequency excitation $n_0 = e^{i\omega t}$. One then obtains $p(\omega) = n/n_0 = \gamma/(\gamma - \omega)$, the complex amplitude transmission ratio, and $P(\omega) = |p(\omega)|^2 = (\alpha^2 + \omega_0^2)/\{\alpha^2 + (\omega - \omega_0)^2\}$ the power transmission ratio. (A quantity having the dimensions of $|n|^2$ will be referred to throughout as a power.)

C_+, C_- real, positive amplitude constants, and

ϕ_+, ϕ_- real phase constants used in representing n as a Fourier series of circular components whose typical terms are $C_+ e^{i[\omega t + \phi_+]}$ (west-to-east) and $C_- e^{-i[\omega t + \phi_-]}$ (east-to-west)

Y_+, Y_- similar amplitude constants, and

θ_+, θ_- similar phase constants representing specifically the annual term in n.

Y_{0+}, Y_{0-} and θ_{0+}, θ_{0-} similarly represent the annual term in n_0.

K is the harmonic number used in Fourier series.

D_+^2, D_-^2, C_{0+}^2, and ϵ defined later, in the discussion of Table 1.

The component with exact annual frequency

can be written in either of two forms

$$Y_+e^{i(2\pi t+\theta_+)} + Y_-e^{-i(2\pi t-\theta_-)}$$
$$= e^{i(\theta_++\theta_-)/2}\{Y_+e^{i[2\pi t+(\theta_+-\theta_-)/2]} + Y_-e^{-i[2\pi t+(\theta_+-\theta_-)/2]}\} \quad (3)$$

The left member of (3) is a pair of circular terms. On the right their combination is shown to be an elliptical motion whose semi-major axis has the magnitude $(Y_+ + Y_-)$, lies in east longitude $(\theta_+ + \theta_-)/2$, and is occupied at time $(\theta_- - \theta_+)/4\pi$.

Fourier series analysis—The data used were 544 values of n at 0.1 year intervals covering the years 1891 through 1945. These were read from the large-scale graphs published by *Kulikov* [1950]. A partial numerical Fourier series analysis was carried through, using the method of *Danielson* and *Lanczos* [1942] with minor modification. The fundamental frequency is one cycle in 54.4 years. Because the data were smoothed most of the power was expected to be below about two cycles per year, that is, in the first 100 harmonics. In fact 93 pct of the total power was represented in the 23 harmonics actually computed, with numbers in the range $40 \leq K \leq 62$. The numerical work was carried through on l and m separately, giving cosine and sine terms for each. These were combined in a straightforward way to obtain the quantities C_+^2, C_-^2, ϕ_+, ϕ_- for circular components which are presented in Table 1, columns 2–5. The power spectrum C_+^2 is also shown by the vertical bars in Figure 2.

The annual component—If a component of exactly annual frequency is present in n, it will show itself in this analysis by substantial contributions, of like phase and known amplitude ratio, to harmonics 54 and 55, and by smaller contributions with 180° alternations of phase in neighboring harmonics both above and below. Behavior of this type is evident in ϕ_+ and less clearly in ϕ_-

TABLE 1 – *Spectrum of variation of latitude*

K	C_+^2	ϕ_+[a]	C_-^2	ϕ_-[a]	D_+^2	D_-^2	Av. D_-^2	$P_{(1\text{ol})}$	C_{o+}^2	Av. C_{o+}^2
1	2	3	4	5	6	7	8	9	10	11
		°		°						
40	2.39	351	0.042	35	2.39	0.042		67	0.035	
41	0.41	220	0.075	206	0.41	0.075		98	0.004	
42	7.43	35	0.177	45	7.43	0.177		159	0.046	
43	8.63	179	0.060	195	8.63	0.060	0.089	292	0.029	0.029
44	0.55	138	0.021	330	0.55	0.021		670	0.001	
45	62.23	187	0.067	114	62.23	0.067		1908	0.033	
46	47.39	265	0.006	355	47.39	0.006		1908	0.025	
47	33.72	298	0.021	213	35.37	0.014	0.027	670	0.053	0.028
48	4.61	168	0.042	125	6.32	0.052		292	0.021	
49	0.91	101	0.082	251	1.01	0.076		159	0.006	
50	1.33	123	0.380	26	2.24	0.325	0.141	98	0.022	
51	0.18	350	0.152	211	1.27	0.111	(0.081)[b]	67	0.018	0.017
52	0.37	311	0.431	50	0.65	0.359		48	0.012	
53	0.09	189	0.009	200	2.06	0.007		36	0.055	
54	26.63	6	0.168	11	0.85	0.036		28.3	0.028	
55	24.52	2	0.302	358	0.85	0.028		22.7	0.035	
56	3.53	169	0.918	139	0.33	0.729	0.203	18.6	0.014	
57	1.91	14	0.084	50	0.24	0.059	(0.032)[b]	15.5	0.012	0.026
58	0.40	165	0.125	124	0.048	0.104		13.2	...	
59	0.62	358	0.166	48	0.072	0.142		11.3	...	
60	0.25	180	0.009	155	0.006	0.004		9.8	...	
61	0.69	3	0.008	326	0.215	0.044		8.6	...	
62	0.42	192	0.056	94	0.113	0.056	0.062	7.6	...	0.003
Sum	229.2	...	3.35	...	180.7	2.55	...	...	...	...
Over-all averages			...	...	...	...	(0.057)[b]	...	...	0.025[c]

[a] $\phi+$ and $\phi-$ are referred to time origin at epoch 1918.7.
[b] Averages excluding K = 50, 52, 56.
[c] Average excluding K = 58 to 62.

TABLE 2 – *Supplementary spectrum values*

Source	K	D_+^2	D_-^2	P(ω₀)	C_{0+}^2	av C_{0+}^2
Data of Table 1	68.0	0.16	0.09	4.1	0.024	
	77.7	0.05	0.02	2.0	0.000	0.012
Pollak [1927]	57.2	0.25	0.08	15.0	0.013	
	60.5	0.24	0.01	9.0	0.020	0.016
Pollak [1927]	68.0	0.44	0.10	4.1	0.092	
	77.7	0.12	0.02	2.0	0.030	0.061

for $52 \leqq K \leqq 62$. Accordingly, the circular terms for n, of exactly annual frequency, shown on the first line of Table 3 were chosen for best fit at $K = 54$ and 55. The calculated contributions of these terms to all harmonics in the range $47 \leqq K \leqq 62$ were subtracted, with consideration of phase, from the total spectrum, to give the residual power coefficients D_+^2 and D_-^2 listed in columns 6 and 7 of Table 1. The annual term is seen to account for a large part of the total power spectrum for $K \geqq 54$.

The corresponding annual term in the excitation n_0 is also given in Table 3. This has been obtained with the use of the transmission factor $P(\omega)$ whose evaluation is discussed in the next section. The elliptical character of these annual oscillations is readily derived from (3). The present formulation makes clear that while the excitation appears to contain components Y_{0+} and Y_{0-} of about the same magnitudes in the two senses, the west-to-east term Y_{0+} is derived from a much more prominent part Y_+ of the response spectrum and is therefore much more accurately established than its companion Y_{0-}. In other words, the difference in semi-axes of the annual excitation ellipse (granted $Y_{0-} > Y_{0+}$) is much better known than its orientation or eccentricity.

Independent values of the annual terms in n were also obtained by a separate calculation carried out directly on the original data, with results shown on the second line of Table 3. The agreement with the first line is not as good as was expected, but no reason for the discrepancy has been found. Results by *Jeffreys* [1940] and *Pollak* [1927] are also given for comparison.

The same calculation shows semi-annual terms with powers $C_+^2 = 0.21$ and $C_-^2 = 0.07$, together being about 0.5 pct of the annual power. These are, however, comparable with the values for a period 0.8 year, for example; the connection with the annual term is therefore doubtful.

An apparent error occurring in Jeffreys' original paper and repeated in his book [*Jeffreys*, 1952] is corrected in Table 3. In the book, one should have at the bottom of page 214, for consistency with page 210,

$$x = -0.090'' \cos\odot + 0.019'' \sin\odot$$
$$y = \quad 0.010'' \cos\odot + 0.073'' \sin\odot$$

giving

$$\lambda = -0.002'' \cos\odot + 0.007'' \sin\odot$$
$$\mu = \quad 0.013'' \cos\odot + 0.034'' \sin\odot$$

The annual component in n is essentially a single line and not accompanied by anything that can be recognized as associated structure.

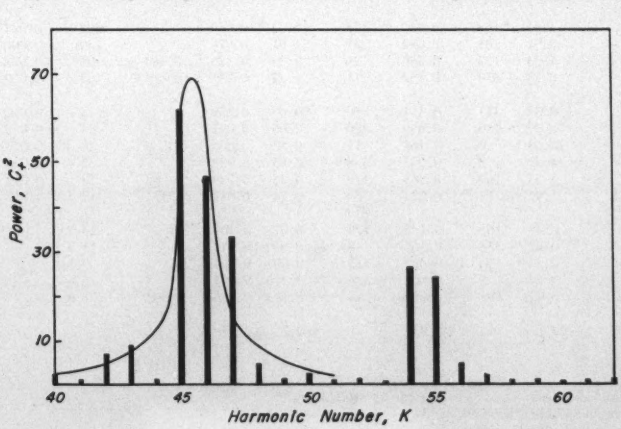


FIG. 2–Power spectrum of polar motion near Chandler and annual frequencies

TABLE 3 - *Annual components*

Source	Polar motion, n				Excitation, n_0			
	Y_+	θ_+	Y_-	θ_-	Y_{0+}	θ_{0+}	Y_{0-}	θ_{0-}
		°		°		°		°
Fourier analysis	8.0	112	0.78	−108	1.57	−75	1.7	−109
Direct calculation	7.6	112	1.00	−105	...	...	...	...
Jeffreys [1952]	8.3	111	0.96	−129	1.63	−76	2.1	−130
Pollak [1927]	8.8	116	1.00	− 84	...	...	...	...

The phase angles are referred to January 1 as time origin.

This point will be discussed further in connection with the continuous excitation spectrum.

The Chandler band—As mentioned in the introduction, the maximum in D_+^2 near $K = 45$ is attributed to a selective response of the Earth in this frequency range. Accordingly, values of center frequency and damping (ω_0 and α) were chosen to produce a power transmission ratio $P(\omega)$ as nearly as possible proportional to D_+^2 in the range $42 \leq K \leq 50$. The curve for $P(\omega)$ so determined is shown in Figure 2 and also in Table 1, column 9, for $\omega > 0$. The roughness of the fit seen in the figure is expected, since the power D_+^2 associated with a single harmonic should be regarded as a random variable possessing a Rayleigh distribution and consequently a standard deviation as great as its expected value. Thus even as much as 54 years of data is strikingly limited in its ability to determine the exact form of the spectrum.

The chosen parameter values are: Chandler period, $2\pi/\omega_0 = 1.196 \pm 0.007$ years $= 437 \pm 2.6$ mean solar days (corresponding to $K = 45.5 \pm 0.25$); amplitude decay time $1/\alpha = 9.5$ years $(+10\%, -20\%)$ (corresponding to half-power half-width $\Delta K = 0.9$). These values and their uncertainties were essentially determined by inspection, though an inconclusive effort at least-square fitting did furnish some guidance. The period is in agreement with previous determinations, but the decay time is materially shorter than reported by *Jeffreys* [1940], his value corresponding to $\Delta K = 0.57$. Jeffreys studied the spectrum through the autocorrelation, and while this approach has equivalent power provided the complete autocorrelation curve is examined [*Rudnick*, 1953], he used only three points therefrom. Consequently, the present result is believed superior.

Values of $P(\omega)$ for $\omega < 0$ range from 0.28 ($K = 40$) to 0.18 ($K = 62$). Though they are not given explicitly in Table 1, use is made of them in the following section.

The continuous spectrum of excitation—If the three greatest values of D_-^2 (east-to-west components of n) in column 7 of Table 1 are ignored (and no interpretation is offered for them) the remainder are fairly flat with frequency, as shown in column 8. These are interpreted as observational error for two reasons. (a) Their magnitude and frequency-independence are reasonable *a priori*. (b) Assuming excitation with circular components of equal amount in the two senses, the theoretical ratio $D_-^2/D_+^2 = P(-|\omega|)/P(|\omega|)$ is far less than observed. Hence the average D_-^2 after the three exclusions, approximately 0.06, is taken as the mean power per harmonic ϵ due to observational error. In so doing we acknowledge impossibility of any direct inference of east-to-west components of excitation from the apparent response terms D_-^2.

For the west-to-east components, however, ϵ was subtracted from each D_+^2 value in column 6 and the result divided by $P(\omega)$ from column 9, giving corresponding terms C_{0+}^2 in the continuous power spectrum of the excitation, n_0, shown in columns 10 and 11. Except for the highest frequencies, $58 \leq K \leq 62$, this calculated excitation spectrum appears flat. In the immediate Chandler region $42 \leq K \leq 50$ this is only a mathematical consequence of the method by which it was obtained. At other frequencies, however, the result is considered significant.

In the region $58 \leq K \leq 62$, the average value of D_+^2 is little greater than ϵ and only an average value of C_{0+}^2 was computed. This is markedly below the average obtained for all lower frequencies. The difference is too marked to be a statistical accident, but is nevertheless considered wholly doubtful, in view of the supplementary values reported in Table 2. Two values of C_{0+}^2 at even higher frequencies based on the same data are possibly consistent with the $58 \leq K \leq 62$ range. But corresponding values from *Pollak* [1927] based on the International Latitude Service data are so markedly different as to make clear that in this sparsely occupied spectral region we are dealing with features of the data which are of doubtful significance, differing radically, as they do, between the Kulikov and the Latitude Service versions of the data. Without a critical restudy of the basic data, including reconsideration of all smoothing processes, it does not seem possible to derive significant values for the excitation spectrum above one cycle per year.

The annual component of excitation is undoubtedly traceable to mean seasonal change in the atmosphere [*Jeffreys*, 1952; *Munk* and *Groves*,

1952]. It is to be expected that the actual cycles of change in successive years will deviate from the mean, displaying amplitude and phase modulation. Consequently the spectrum line of one cycle per year frequency should be accompanied by side-band power, very probably distributed symmetrically above and below the annual line, and extending over the frequency range (1 ± 0.5) cycles per year, $27 \leq K \leq 82$. This appears the most plausible source, and perhaps the only plausible source, for the continuous spectrum of excitation which furnishes the energy dissipated by the Chandler component of n, the motion of the rotation axis.

Two tests may be used in considering whether the continuous excitation power below one cycle per year shown in column 11 of Table 1 is in fact a lower side-band of the annual line and consequently attributable to the atmosphere. First is its relative magnitude. This is about one pct of the annual line per harmonic or possibly 27 pct over the region of the side-band, which is reasonable. A second test is the existence of an upper side-band located symmetrically above the annual frequency. The evidence, unfortunately, is inconclusive, as pointed out in the foregoing.

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The Establishment of an International Gravity Standard

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Abstract—A program of pendulum and gravimeter measurements for the establishment of a gravity standard between Mexico and Alaska is described. The problems involved in obtaining precise measurements with pendulums are discussed, values for three independent sets of pendulum measurements and gravimeter measurements are compared.

Introduction

General statement—In the course of establishing a network of gravity bases throughout the world [*Woollard*, 1949], it was found that not only were there discrepancies in the national gravity-base values, but also that the reference gravity standards used were not consistent. Because of this lack of uniformity in gravity standards in use and its effect on the calibration of gravimeters, there is a potential difference in long-range gravimeter measurements that amounts to over 20 mgal between the polar regions and the equator. The reason why the calibration standards used are not uniform has been discussed in a previous paper [*Woollard* and others, 1955]. This paper deals with the program initiated in 1949 to establish a gravity reference standard based on precision pendulum measurements having sufficient range (4500 mgal) to check the over-all linearity of modern geodetic-type gravimeters and to furnish a calibration good to one part in 10,000 ($\pm$0.5 mgal for a change of 5000 mgal).

Equipment used—In making the measurements the writers were fortunate in securing the use of three sets of the compound quartz pendulums of the Gulf Research and Development Co. These pendulums differ from most others in common use in that (1) they are not affected by changes in the Earth's magnetic field, (2) they are minimum pendulums and, as a result, their period is not affected by knife-edge wear as much as that of the invariable pendulums commonly used, and (3) they are operated at constant temperature and are maintained in a sealed case throughout a field season; hence, they are operated under the same conditions for each observation. Most important, they have a history of maintaining an operational precision of $\pm$0.25 mgal in the field. A complete description of these pendulums is given by *Gay* [1940]. Supplementary measurements were made using both North American and Worden gravimeters.

The North American Gravity Range

General plan—In planning the location of the observation sites, ease of accessibility was considered to be as important as the changes in gravity involved. A good road system extends from the Guatemala-Mexican border to Fairbanks, Alaska, but a greater change in gravity can be obtained using air transport between Point Barrow, Alaska, and Quito, Ecuador. Since it was felt that accessibility both by road and air was desirable, a search was made for a suitable southern terminus in Mexico having a minimum gravity value. The first choice was in the crater of Mt. Toluca near Mexico City. This site has a gravity value equivalent to that of a point at sea level in Colombia, South America. However, because of operational difficulties this site was abandoned after the first attempt to occupy it using the pendulums, and the Paso Cortez television station outside Mexico City was adopted in its place. The northern terminus selected was at Fairbanks, Alaska. The intervening observation points follow the Pan-American highway to San Antonio, Texas, with a diversion to Houston in order to follow the principal air route; then north through Amarillo along the Rocky Mountain front to Edmonton, Alberta. From this point the route follows the Alaska Highway to Fairbanks. Observations were to be made either at the major airports along the way or at sites which could be tied by gravimeter connections to the airports. It would thus be possible to take continuing airplane flights and make observations for calibration purposes during the ten to fifteen minute stops at each airport. The entire range could, in this way, be run with closures in about ten days.

As one of the major difficulties to be anticipated on an extended series of measurements of this type is the occurrence of sudden changes in pendulum period because of crumbling of the pendulum knife edges, a companion series of gravimeter measurements was also planned. These measurements would serve to detect and localize any major discrepancies in the pendulum measurements.

Program development—The program was ini-

tiated in 1949 and a series of gravimeter measurements established from Great Falls, Montana, to Fairbanks, Alaska. These measurements were made using road transport with a high-range North American gravimeter loaned to the project by the Cambridge Airforce Research Center. Observations were made at about 100-mile intervals on one leg and at 12 to 15 mile intervals on the other. The over-all change in gravity between Mexico City and Fairbanks was checked that same year using a Worden gravimeter and air transport. In the course of making these observations, the pendulum stations of the U. S. Coast and Geodetic Survey and of the Dominion Observatory of Canada along the route, were occupied to see to what extent the values for these sites might be incorporated into the calibration standard. It was found that on the average the two sets of data only agreed to about ±3 mgals (see Fig. 1). However, as an earlier study of the pendulum values in the United States and Canada [*McCollum*, 1943] had indicated much less spread than that found by the writers, a second series of measurements using a Worden gravimeter was carried out between Madison, Wisconsin, and Fort St. John, British Columbia, in 1950. These measurements corroborated the accuracy of the earlier gravimeter measurements, as shown in Figure 2. It was, therefore, concluded that the existing pendulum data were too inaccurate to be used.

The first Gulf pendulum equipment used (Set C) was a set on loan to the Lamont Geological Observatory of Columbia University. However, this equipment had not been used for a number of years, and it required considerable overhauling. In addition a new crystal-controlled chronometer and recorder had to be built before any field measurements could be undertaken. As a result no pendulum measurements other than tests were carried out prior to 1951.

In the interim the U. S. Coast and Geodetic Survey, using the Brown pendulum equipment [*Swick*, 1942] established a line of pendulum and gravimeter measurements for calibration purposes between Fort Sam Fordyce, Texas, and The Pas, Manitoba. These measurements lay about 500

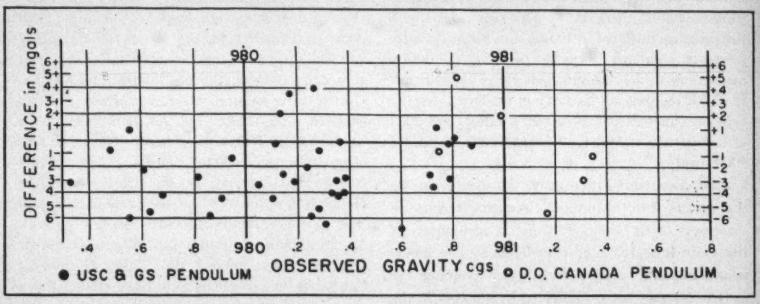

FIG. 1 – Difference plot, North American gravimeter 113 and pendulum values, United States and Canada

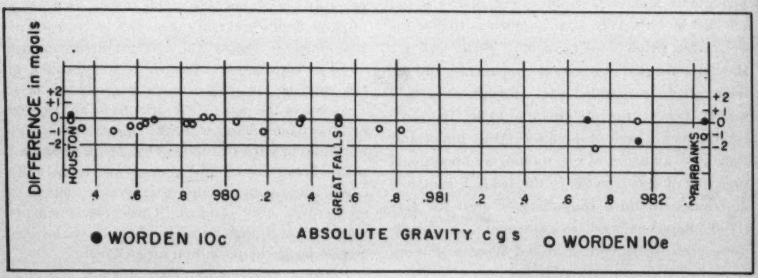

FIG. 2. – Difference plot, North American gravimeter 113 and Worden gravimeters 10c and 10e

miles to the east of those planned and the change in gravity involved was a little over 2000 mgal. Since, at that time, the writers had only succeeded in establishing gravimeter values over their line of proposed pendulum observation sites, it appeared logical to modify the original site plan and to observe with the Gulf pendulums in the United States at these bases established by the U. S. Coast and Geodetic Survey. This would give an independent set of pendulum measurements at the same sites and presumably strengthen the values. However, as the earlier analyses of older pendulum values (Figure 1) had shown such large random errors in the results obtained with the U. S. Coast and Geodetic Survey pendulum equipment, the writers felt that before changing their plan, the accuracy of these new pendulum measurements should be evaluated. Therefore, in 1951, four high range gravimeters, a Frost, a North American, and two Worden meters were run over that portion of the

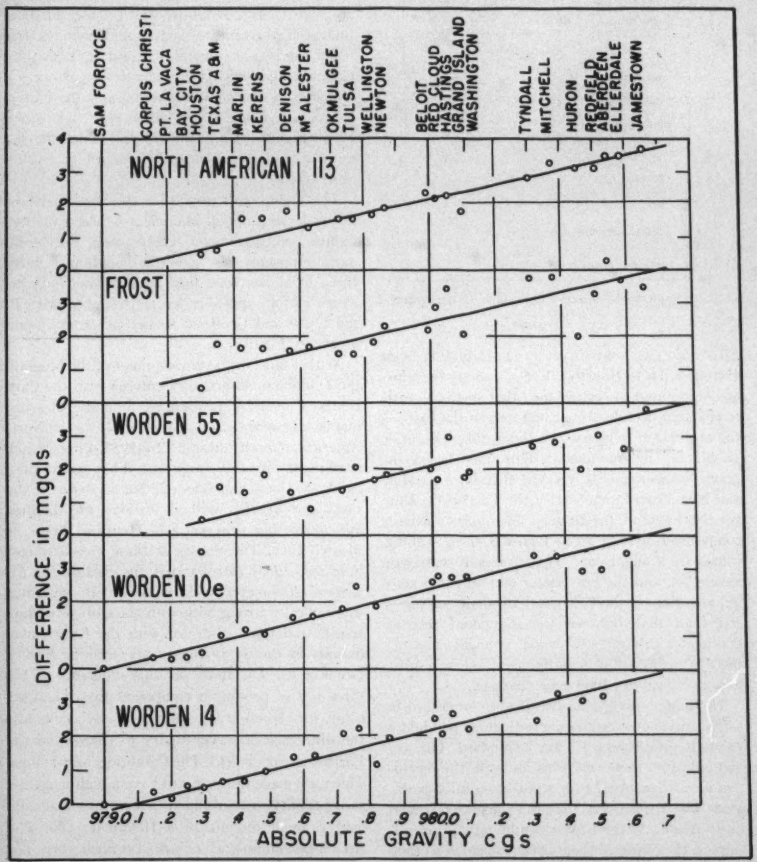

FIG. 3 – Difference plots, gravimeters and pendulum values; gravimeters calibrated on Cambridge pendulums, USC&GS pendulums (1950 values)

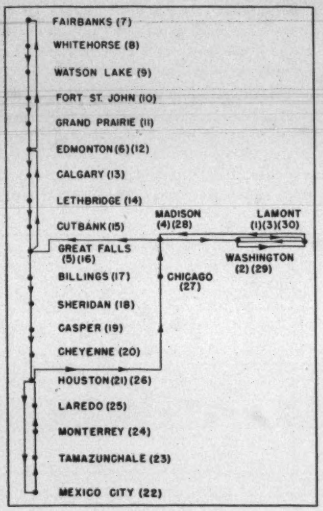

FIG. 4 – Sequence of observations, Gulf C pendulums, 1951

Coast and Geodetic Survey range extending from Huron, S. D. to Houston, Texas, and two gravimeters were used to occupy the other stations south of Houston. Results were computed on the basis of the calibration being used on the world program of gravimeter measurements. This was based on gravity measurements in Great Britain, Australia, and New Zealand made with the Cambridge University (England) pendulums. The results for these comparisons are shown in Figure 3. Two striking things are brought out: (1) the random scatter of values between the gravimeter and adjusted pendulum values of the Coast and Geodetic Survey is less than that between the individual sets of gravimeter values (±0.3 mgal average), and (2) there is a marked systematic deviation in results, over two mgal per 1000 mgal change.

The first showed the advantage to be gained in using gravimeter values for adjusting pendulum values in establishing a gravity standard. The second indicated there was some factor in the pendulum measurements that was not being fully evaluated. The writers felt that this factor was most likely related to the Brown pendulum equipment, since in the course of their world comparisons they had not observed a similar deviation in other pendulum values. As a second set of pendulum values differing significantly from the original ones would lead to confusion, it was decided to follow the original plan to make the measurements with the Gulf pendulums in the United States along the Rocky Mountain front. Accordingly, in the late summer of 1951, measurements were started with the Gulf pendulums. Observations were made in Washington, D. C., and Madison, Wisconsin, en route to Great Falls, Montana, from which point the range proper was followed to Fairbanks, Alaska. Closures were taken at Edmonton, Alberta, and Great Falls, Montana, and the measurements then carried south to Cheyenne, Wyoming, from which point they jumped to Houston, Texas; then resumed to Mexico City with return closures at Houston, Madison, Washington, and the Lamont Geological Observatory [*Woollard* and others, 1953]. Figure 4 shows the order in which the sites were occupied and the points at which closures were taken.

The preliminary results for this work indicated rather large random differences between the pendulum and gravimeter values (±1 mgal), but more important, a systematic deviation of nearly three mgal per 1000 mgal change was indicated which had an opposite sign to that observed with the Coast and Geodetic Survey pendulum equipment (see Fig. 5).

At this stage in the development of the program, the Dominion Observatory entered with the Cambridge University pendulums to make measurements over what was now referred to as the North American Gravity Range. In 1952, observations were made with this equipment at key points along the U. S. Coast and Geodetic Survey series of stations and at the writers' stations at Madison, Wisconsin, and sites south of Houston, Texas, to Mexico City. The results of these measurements [*Garland*, 1953] corroborated the findings of the writers' gravimeter work, namely that something was radically wrong both with the Gulf pendulum results and those obtained with the Brown pendulums by the U. S. Coast and Geodetic Survey (see Fig. 6). The most obvious difference in the three sets of pendulum equipment that might account for the observed systematic deviations was the difference in susceptibility to changes in the Earth's magnetic field. The Cambridge pendulums, which are made of invar and have a high magnetic susceptibility, are swung in a constant magnetic field through the use of a Helmholtz coil. The Brown pendulums, which are also invar, were not magnetically compensated. Since the sign and magnitude of the observed difference in results ob-

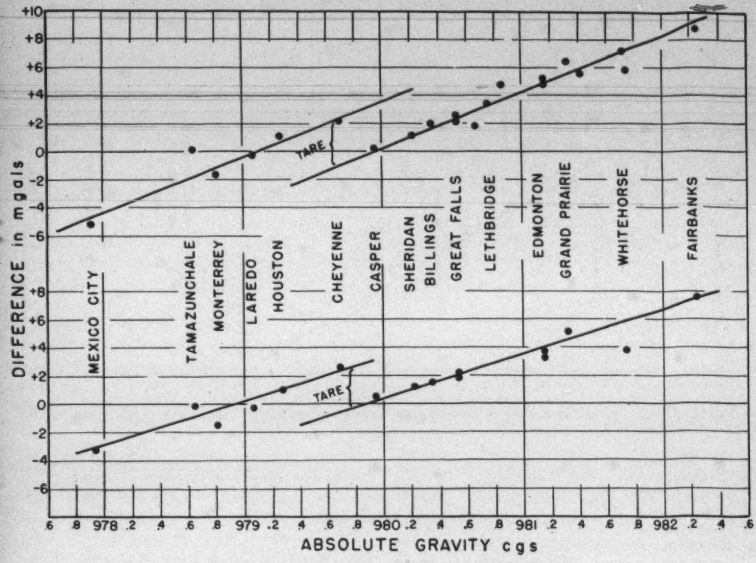

FIG. 5 – Difference in Gulf pendulum and gravimeter values; (a) Gulf C pendulum and North American gravimeter; (b) Gulf C pendulum and Worden gravimeter

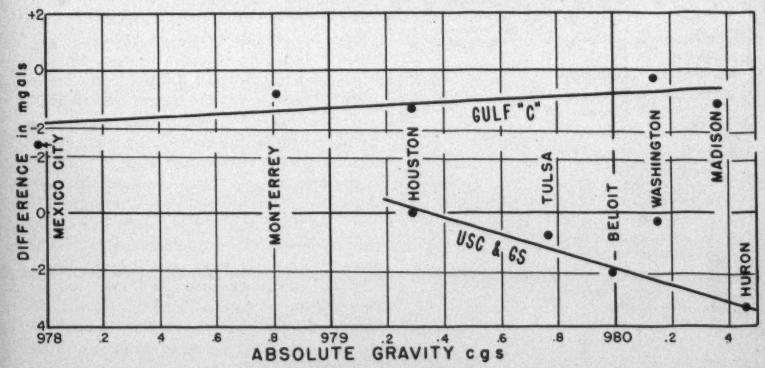

FIG. 6 – Comparison of Gulf C pendulums (1951 value) and USC&GS pendulums (no magnetic compensation) with Cambridge pendulums

tained with these two sets of pendulums was of the order to be expected for this effect, it appeared that the Coast and Geodetic Survey differences could be eliminated through the use of a Helmholtz coil. In the case of the Gulf pendulums, which are inherently non-magnetic, the cause of the deviations observed was not obvious. At first it was believed to be related to knife-edge wear, but as shown in Figure 7 there was no correlation of the differences with time but rather a marked correla-

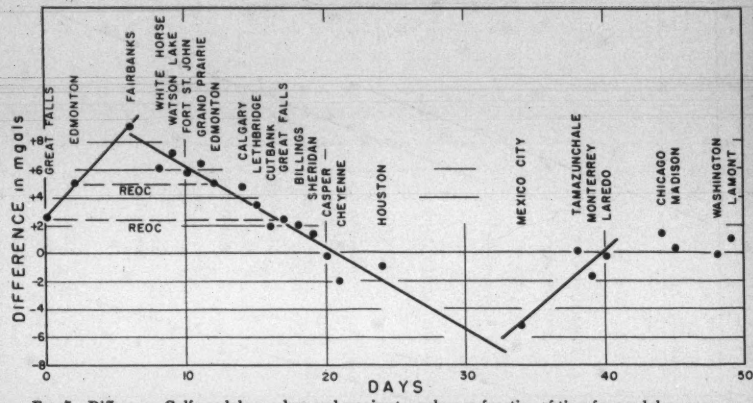

FIG. 7 – Difference, Gulf pendulum values and gravimeter values as function of time for pendulum survey

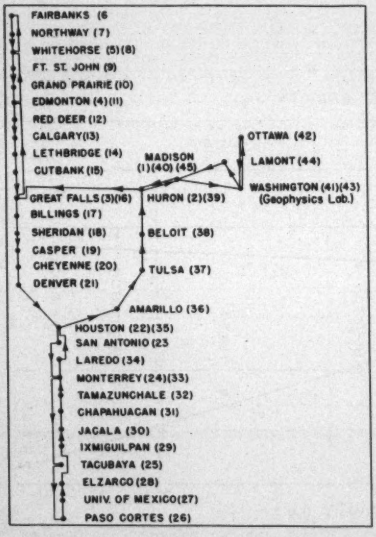

FIG. 8 – Sequence of observations, Gulf pendulums, 1953

tion with latitude. In 1954 it was established that this relationship was caused by ionospheric and distance effects on the strength of the WWV time signals and the method used in rating the crystal chronometer. A reinterpretation of the chronometer rate graphs for the 1951 work [*Woollard* and others, 1954] eliminated this pseudo-latitude effect.

In the meantime two additional sets of Gulf pendulums were secured from the Gulf Research and Development Company (sets K and M) which were regarded as superior to the C set originally used. Observations were again made with both of these sets of equipment in 1953 over the entire series of sites from Fairbanks to Mexico City. Key stations of the Coast and Geodetic Survey series of stations also were occupied between Houston, Texas, and Huron, South Dakota, and a tie established between Washington and Ottawa [*Woollard* and others, 1954]. On these measurements the method of rating the chronometer was changed (described later) since it was suspected that the discrepancy in the 1951 measurements might have this source. Figure 8 shows the 1953 program. This same year, the Dominion Observatory occupied the northern half of the range from Lethbridge, Alberta, to Fairbanks, using the Cambridge pendulums and also gravimeters. The U. S. Coast and Geodetic Survey, using a Helmholtz coil with the Brown pendulums, also observed at the same key stations of their series of bases occupied with the Gulf and Cambridge pendulums and, in addition, occupied the Fairbanks, Alaska station, and established four other Alaska stations between Kodiak and Point Barrow.

Comparisons of preliminary values showed that the three types of pendulum equipment were then giving results that were in essential agreement, although there did appear to be a difference between the Cambridge and Gulf pendulum values of

about one mgal for the northern and southern halves of the line. To determine if this offset was related to a tare (jump) in observations, repeat observations were made in 1954 with the M set of Gulf pendulums at a series of stations that would bridge the gap between the 1952 and 1953 measurements with the Cambridge pendulums, and also give a direct triangle closure on the center of the Gulf pendulum line. Starting from Madison, Wisconsin, observations were made at Huron, South Dakota; Great Falls, Montana; Edmonton, Alberta; and Houston, Texas, with closures at Great Falls, Huron, and Madison. A new tie was also run from Madison to Washington and Ottawa with closures at Washington and Madison, and two supplementary sets of gravimeter measurements made covering the entire range from Mexico to Alaska [*Rose* and *Woollard*, 1955]. Figure 9 shows the locations at which observations have been made in North America.

A similar series of measurements was initiated in 1954 to extend from Norway to South Africa, and from Japan ultimately, it is hoped, through Australia. Foreign sites occupied to date by the writers with the Gulf pendulums include Honolulu, Hawaii; Tokyo and Kyoto, Japan; Manila, P. I.; New Delhi, India; Oslo, Norway; Copenhagen, Denmark; Bad Harzburg, Frankfurt, and Munich, Germany; Teddington, England; Rome, Italy; Tripoli, Lybia; Cairo, Egypt; Asmara, Eritrea; Khartoum, Sudan; Nairobi, Kenya; Victoria Falls, Southern Rhodesia; Lusaka, Northern Rhodesia; Johannesburg and Capetown, Union of South Africa.

FIG. 9 – Location of pendulum bases with Gulf pendulums in North America

FACTORS INFLUENCING THE ACCURACY OF PENDULUM OBSERVATIONS

General statement—The factors that control the ultimate accuracy of any set of pendulum values can be divided into those associated with design of the equipment, those related to external or special factors, those related to operational procedure and those related to methods of reduction.

The essentials of each can be summarized as follows:

A Factors that are inherent in the design of the equipment: (1) Type of material used for the pendulum; (2) flexure (sway) of pendulum support; (3) observation of flexure; (4) amplitude of oscillation; (5) maintenance of pressure; (6) observation of pressure; (7) maintenance of temperature; (8) observation of temperature; (9) rating of chronometer; (10) chronometer stability; and (11) recording pendulum oscillations relative to elapsed time.

B Factors of external or special origin: (1) changes in external magnetic field; (2) changes in ambient temperature; (3) changes in pendulum length due to molecular readjustment; (4) changes in moisture content of air; (5) seismic effects; (6) dissipation of electrostatic charges; (7) wear of knife edges; and (8) induced resonance in base.

C Factors related to operational procedure: (1) establishment of thermal equilibrium; (2) sealed vs. unsealed case observations; (3) duration of runs; (4) number of repeat runs made; and (5) closures obtained.

D Factors related to method of reduction: (1) sampling of record; and (2) method of distributing closure errors.

It is not the writers' purpose to give a complete discussion on each of these factors so much as to point out those conditions that are apt to produce significant errors. The following discussions therefore will be brief.

Effect of type of material used—Three materials have been used for the construction of modern pendulums: bronze, invar, and quartz. Each has certain desirable as well as undesirable qualities. Bronze is non-magnetic and hence not affected by changes in the Earth's magnetic field, but it has a high thermal coefficient of expansion. Corrections for changes in temperature are, therefore, appreciable unless the pendulums are swung at constant temperature in a heated, thermostatically

controlled case. This has not been done, and the accuracy of results obtained with bronze pendulums in large measure reflects the accuracy with which their temperature coefficient is established, the degree of thermal stability maintained during a run and the range of temperatures involved at the observation sites.

Invar pendulums while possessing a low thermal coefficient of expansion have two defects. Invar is not always stable with respect to length, and it is also ferromagnetic. The latter effect results in systematic errors in values that are related to changes in magnetic latitude unless some type of magnetic compensation is employed. As indicated earlier, to guard against this effect, a Helmholtz coil is now used both with the Cambridge University Invar pendulums and with those of the U. S. Coast and Geodetic Survey. The stability characteristics of an invar pendulum can only be determined through use, and in this respect the Cambridge pendulums appear to be excellent.

Quartz pendulums while on the whole very stable do appear to be subject to some adjustment after having been on the shelf for long periods of time. They are non-magnetic and possess a low thermal coefficient of expansion, but they have one defect in that they develop electrostatic charges which will affect their period if some provision is not made for discharging them. With the Gulf pendulums, this is accomplished by placing a radium salt in the case which ionizes the medium and thus provides a conductor for dissipating the induced charges.

Flexure of pendulum support—A single pendulum oscillating on a support will induce a sway in the support that influences the observed pendulum period. If two pendulums, however, are swung on the same support 180° out of phase, the induced motion from each will tend to cancel out and there will be a minimum of flexure of the support. This latter system is employed with the Vening-Meinesz submarine pendulum apparatus, the Cambridge University pendulums, and the Gulf pendulums. With single pendulum systems, as those of the U. S. Coast and Geodetic Survey, interferometer observations are required in order to determine the flexure of the support so that a suitable correction can be applied to the observed pendulum period.

Flexure may also be observed with an independent pendulum at another place on the supporting framework. This pendulum is at rest when the observations start and the motion imparted to it during the course of a run can be used to determine the amount of flexure.

Amplitude of oscillation—The determination of the initial and final amplitude of oscillation on a run is critical and an error of 0.5 mm in measuring the arc of swing will result in errors of a mgal. With the Gulf pendulum equipment both pendulums are mechanically cocked and released simultaneously with very nearly identical starting amplitudes at all stations; with most other pendulums the starting amplitude is more variable and the corrections, therefore, more important.

Pressure in case—All pendulum observations are carried out in a partial vacuum. Sources of error are of four types: (1) those related to the operating pressure, (2) those related to changing pressure because of leakage, (3) those related to a variable percentage of water vapor present, and (4) those related to pressure measurement. With all pendulums the pressure-correction coefficient is applied as a linear function and experimental results show that this holds at pressures above one mm of mercury. At lower pressures, because of factors not completely understood, this linear coefficient no longer holds. As a result, observations are usually made in the pressure range from two to five mm of mercury. If there is a pressure leak in the case, the problem of determining the mean effect on the pendulum period due to the changing pressure raises an uncertainty as to the exact pressure correction to be applied. If it is assumed that the mean correction corresponds to the mean velocity of the pendulum and hence to the time when the amplitude has its mean value, then the pressure corresponding to the mean pressure correction on a one-hour run should be taken slightly prior to 30 minutes; for the Gulf pendulums, this was calculated to be 28.5 minutes. Since the Gulf pendulum has a larger surface area than most others, and the effect on the period of taking the pressure at 28.5 minutes, rather than 30 minutes, is negligible, the effect is probably negligible for other pendulums also.

The effect of water vapor on the pressure coefficient is appreciable, and the effect will vary with the differences in moisture content. Tests conducted by the writers with the Gulf pendulums indicated a decrease of five per cent in the pressure coefficient for runs made with dry air over that obtained with air having a normal moisture content. To guard against this effect, all runs with these pendulums are currently made with a desiccating agent in the case.

The greatest potential source of error in regard to pressure, however, is related to the accuracy of its measurement. If a manometer is used, the accuracy with which it can be read is related to its bore. In order to secure an accuracy of 0.1 mm, the

bore has to be about one cm. As the manometer zero is critical in establishing what the case pressure actually is, it must be constantly checked in order to make sure there has not been any air entrapped with a consequent change in the zero value. On the runs with the Gulf pendulums to Alaska in 1951, a shift in the manometer zero developed that resulted in an uncertainty of about 1.0 mgals in the results.

The use of a McLeod gage or other precise pressure measuring device improves results and with instruments such as the Gulf pendulums, which are more sensitive to pressure effects than most other pendulum equipment, such gages are now being used.

Operational temperature—On all instruments except those maintained at constant temperature, the corrections for changes in temperature constitute a major potential source of error. This is because of the appreciable effect of a small change in temperature on the pendulum period and because of the large variations in temperature encountered. The problem is complex in that not only is the effective length of the pendulum involved, but also the buoyancy of the medium and the frictional drag on the moving pendulum. Since the case is evacuated, it takes a while for thermal equilibrium to be reached and this may be as much as 12 hours. With instruments such as the Gulf pendulums, which are operated at a constant temperature (110° F), this time lapse before making measurements can be eliminated by keeping the pendulum case up to operating temperature while in transit. It was observed when this was not done, that even after the internal thermometers indicated the operating temperature had been reached and maintained for as much as two hours, errors of the order of 2.0 mgal could be obtained because thermal equilibrium was not complete.

Chronometer—Whereas in early pendulum work, spring-wound chronometers had to be used which were rated by telegraph and later by radio time signals, most measurements are now made using a crystal-controlled, synchronous-motor clock. Methods of rating the chronometer, though, have a marked effect upon the accuracy obtained. For example, in the 1951 program of gravity observations carried out by the writers, the pendulum chronometer was rated by using the one-second interval 1000 cycle marker pulses transmitted by WWV to fire a strobotron circuit. (The WWV pulse consists of five cycles of a 1000 cycle per second frequency.) This illuminated the shutter disk used to put time marks on the photographic record and allowed scribed marks on its surface to be compared against a fixed scale. At distances beyond the ground path for the WWV radio signal, where travel was via a reflected path from the ionosphere, offsets on the chronometer rate graph up to 10 milliseconds were observed, as indicated in Figure 10. These offsets were attributed at first to difference in travel path because of shifts in the ionospheric reflecting layers. It later developed that these apparent changes in travel time were actually related to distortion of the received marker pulses so that the amplitude of the first cycles of the pulse were too weak to trigger the strobotron circuit. At remote sites it frequently was not until after the arrival of the second or third cycle of the pulse that the signal built up sufficiently to trigger the strobotron. This error in rating the chronometer induced errors in excess of 2.5 mgals in the results and also gave an apparent systematic change with latitude that was entirely fictitious. The system now being used with the Gulf and the Cambridge pendulums is to rate the crystal chronometer oscillator against the WWV carrier frequency. This method eliminates the difficulties associated with the original method. This, unfortunately, does not give a direct check on the rate of the synchronous motor, and it must be assumed that the motor is a perfect slave to the oscillator. This assumption, however, appears to be justified when using a non-selfstarting motor.

Recording of pendulum oscillations—In modern pendulum work most equipment utilizes photographic recording of the pendulum oscillations and time marks which are superimposed on the same film or photographic paper strip. The accuracy of determining the period is thus subject only to errors from variable film speed and film shrinkage after development. In general, this is not considered to be serious.

Seismic effects at base—Ground vibrations are inherent in some regions because of geological factors, such as local volcanic or seismic activity. Ground vibrations also may be induced by traffic where the area is one of unconsolidated materials. Another type of vibration is that induced in a concrete slab floor or a columnar pier by the oscillations of the pendulum itself. Errors having this source are difficult to evaluate, but on the basis of the observations made by the U. S. Coast and Geodetic Survey in studying differences in results obtained on and off the gravity piers in the Commerce Building, errors of the order of 2.0 mgal or more are possible.

Wear of knife edges—Although all pendulum knife edges are aged by swinging for many hours before any field observations are attempted, there

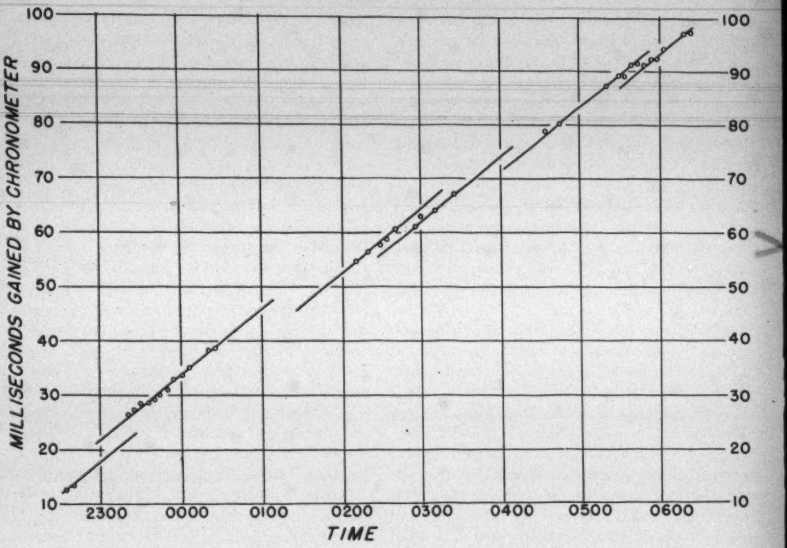

FIG. 10 – Fictitious ionosphere effects in rating chronometer caused by delay in Strobotron firing

is a certain amount of wear in the field. This appears to take place mostly as abrupt crumbling of the vitreous knife edges, giving rise to instantaneous changes in period of the pendulum. The best way to detect where abrupt changes take place is to run a series of gravimeter measurements as a companion survey along with the pendulum observations. Comparisons between the two sets of results will thus indicate where tares were obtained. Although this procedure will not necessarily indicate which set of data is in error, if periodic closures are also taken with both sets of instruments, it is possible to pinpoint the locations at which trouble is encountered. In the 1951 measurements one such tare of 2.9 mgal was obtained at the Casper, Wyoming, site.

Instability in pendulum length—Apparently the effective length of the pendulum can change because of factors not understood; whether this is related to knife-edge wear or the pendulum is not known. Two effects have been noted with the Gulf pendulums. On the first stations after the base observation when the pendulum equipment has been out of use for several years, or when adjustments have been made within the case, there is apt to be a change in effective length. Experience has indicated that, if some sort of a shakedown trip is not taken before starting a field program, a tare of more than one mgal can be expected on the first field station. The other change noted is that one pendulum will gradually change its effective length throughout a field season. The over-all effect of a change of this latter type is illustrated in Figure 11 which compares the observed periods of the pendulums in the Gulf C equipment at the beginning and end of the 1951 season. It is seen that whereas the period of the No. 1 pendulum remained essentially constant, that for the No. 2 pendulum increased sufficiently to give an offset in the mean value of the fictitious pendulum period of 2.2 μS (4.4 mgal).

Open case operations—Where multiple pendulums are used the case must be opened in order to change pendulums. There are several attendant disadvantages and advantages to this system. The principal disadvantages are the possibility of dust particles getting into the case, changes in effective length of the pendulum, and variations in the density and viscosity of the medium because of changes in ambient temperature and humidity. With a sealed system, in which the case is never opened during the course of a survey, only variations in temperature are encountered, and these can be eliminated by operating at constant tem-

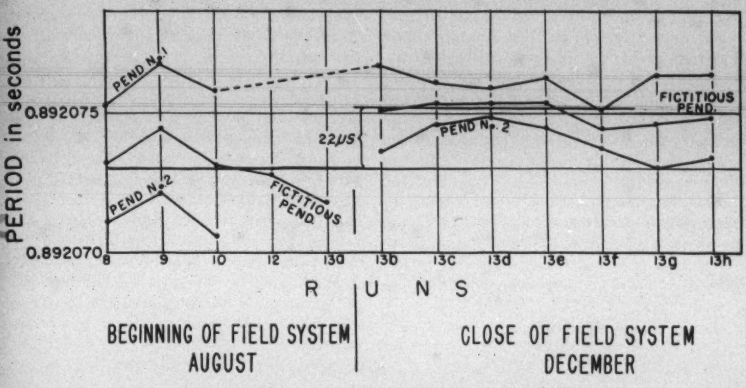

FIG. 11 – Effect of instability of length of pendulum

perature with a thermostatically controlled heating jacket. A disadvantage of the sealed system is that no more than two pendulums can be used. With the multiple pendulum system it can be argued that a better statistical average can be determined through the use of several pendulums, and, as the pendulums are transported separately, they can be better safeguarded against damage in transit. An opposing argument to the latter point, however, is that with so much handling of the pendulums the chances for damage are greater than in a sealed case where they are held off the knife edges in a set of clamps. The principal effect that the writers have observed with the Gulf pendulum is that after opening the pendulum case the pendulum periods usually show a decrease of several parts per million. The cause of this irregularity, however, is not known.

Number of runs—There is little doubt that a number of runs is preferable to a single run. A slight skewness in setting the pendulums down on the bearing plate may result in an error of a mgal or more. To avoid such effects, the writers make it a practice to take three runs of several swings each with the pendulums being lifted and reset between each run. Variations in period between individual swings may exceed 0.5 mgal, but the average for any series of runs is found to be about ±0.2 mgal.

Duration of runs—The duration of a run should be governed by the accuracy of the timing system. With a well-rated crystal-controlled chronometer permitting time to be determined with an accuracy of one part in 10^8, an hour period will be sufficient. A three-hour run with an inferior time standard, on the other hand, might not be long enough to obtain a reliable measurement.

Closures—The importance of closures has already been mentioned in connection with the change of pendulum period because of knife-edge failures. The early practice of taking closures only at the end of a season's operations would result in considerable errors unless multiple pendulums were used, since there would be no clue as to where a pendulum changed period. Under such conditions, a closure error would have to be distributed over all

TABLE 1 – *Comparison of gravity intervals; Gulf pendulums and Gravimeter W10f (Gulf pendulum calibration)*

Station	Mgals difference from Houston Technical Laboratory			
	Gulf M	Gulf K	Gulf C	W10f
Alaska				
Fairbanks	+2945.6	+2945.5	+2946.5	+2946.5
Canada				
Whitehorse	+2450.4	+2450.5	+2449.3	+2450.6
Fort St. John	+2106.5	+2106.8	+2108.3	+2107.0
Edmonton	+1869.7	+1869.7	+1870.0	+1869.6
United States				
Cutbank	+1309.4	...	...	+1310.5
Great Falls	+1228.2	+1227.9	+1228.5	+1228.5
Billings	+1071.8	+1071.2	+1071.6	+1072.6
Casper	+656.5	+657.2	+656.7	+657.6
Denver	+312.2	+311.9	...	+313.3
Amarillo	+125.2	+128.1	...	+124.9
Houston	0	0	0	0
Mexico				
Monterrey	−493.3	−493.3	−492.6	−492.9
Tamazunchale	−638.8	−638.4	−637.3	−638.9
Chapulhuacan	−813.9	−814.2	...	−814.2
Ixmiquilpan	−1130.1	−1131.3	...	−1130.4
Tacubaya	−1356.9	−1355.7	−1355.7	−1356.8
El Zarco	−1530.6	−1530.5	...	−1530.9
Paso Cortes	−1727.6	−1726.9	...	−1727.6

the observations, and this would introduce errors where there were none and only partially correct for errors where they were real. Although a leap-frog system of pendulum observations would be best for maintaining a rigid control on an extended series of measurements, economic considerations make it more feasible to carry out a companion gravimeter survey for allocating tares (jumps) in the measurements.

Record sampling—Since it is not feasible to analyze each oscillation of the pendulums, the record must be sampled. In general this is not regarded as a problem since current practice appears to cover a record adequately in determining the average period.

Unknown effects—In addition to the above factors which are recognized and whose effects have been evaluated, there are random variations which occur that can not be correlated with any known factor. For example, of the five connections that have been made between Washington, D. C., and Madison, Wisconsin, with the Gulf M set of pendulums, four agree to ±0.2 mgal, but one set of measurements consisting of four multiple runs of three swings each, conducted under apparently identical conditions, differs by over one mgal from the average of the others. In an effort to determine what factor might be associated with such erratic variations, a series of laboratory tests are still in progress.

TABLE 2 – *Base connections relative to Geophysical Laboratory, Washington D. C. (980.1007 cgs)*

Station and observation	Interval	Remarks
	mgal	
Science Hall, University of Wisconsin, Madison, Wis.		
M pendulums (1)	268.6	One lowering
(2)	268.4	One lowering
(3)	268.5	Av. of four lowerings
(4)	267.3	Av. of three lowerings
(5)	268.7	Av. of three lowerings
K pendulums (1)	267.8	One lowering
(2)	267.6	One lowering
Weighted average interval value	268.3	g = 980.3690 cgs
Gravimeter interval using Gulf calibration	268.2	
Dominion Observatory, Ottawa, Ontario, Canada		
M pendulums (1)	520.3	One lowering
(2)	520.5	Av. of four lowerings
K pendulums, 1953 (1)	518.9	One lowering
Weighted average interval value	520.2	g = 980.6209 cgs
Gravimeter interval using Gulf calibration	520.3	

RESULTS OBTAINED WITH THE GULF PENDULUMS

As indicated earlier the results obtained for the measurements made in 1951 with the Gulf C set of pendulums showed a systematic deviation with latitude from the gravimeter values because of an erroneous interpretation of the chronometer-rate graphs. These values have been recalculated on the basis that there was no significant change in travel path for the WWV time signals while at any one station. Although the details of these recalculations are reported elsewhere [*Woollard* and others, 1954] final values are listed in Table 1 for comparison with the 1953, 1954 values. This comparison shows that on an over-all basis the 1951 results are in reasonable agreement, with the later more precise work. All values, however, are not of

TABLE 3 – *Comparison of gravity intervals, Gulf, Cambridge, USC&GS (Brown) Pendulums and Gravimeter W10F*

Station	Gulf C	Gulf K	Gulf M	Cambridge	USC&GS	W10f
Ottawa-Madison	...	−251.2	−252.2[a]	−252.6	...	−252.1
Madison-Beloit	...	−370.1	−370.3	−370.6	...	−370.8
Madison-Huron	...	+84.5	+84.4	+85.9	...	+85.2
Huron-Beloit	...	−454.6	−454.7	−456.5	−456.1	−456.0
Beloit-Tulsa	...	−229.9 (rejected)	−232.0	−232.6	−232.5	−231.3
Tulsa-Houston	...	−470.2 (rejected)	−468.4	−467.4	−468.5	−468.6
Huron-Houston	...	−1154.7	−1155.1[a]	−1156.5	−1157.1	−1155.9
Madison-Houston	−1070.4	−1070.2	−1070.7[a]	−1070.6	...	−1070.7
Houston-Monterrey	−492.6	−493.3	−493.3	−493.5	...	−492.9
Monterrey-Mexico City	−863.1	−862.4	−863.6	−864.0	...	−863.9
Houston-Mexico City	−1355.7	−1355.7	−1356.9	−1357.5	...	−1356.8
Houston-Fairbanks	+2946.5	+2945.5	+2945.6	+2946.9[b]	+2947.5	+2946.5
Madison-Edmonton	+799.6	+799.5	+799.0	+799.5[b]	...	+798.9
Edmonton-Fairbanks	+1076.5	+1075.8	+1075.9	+1076.8[b]	...	+1076.9

[a] Average values based on multiple observations made on two series of measurements (1953 and 1954).
[b] Provisional values; courtesy, Dominion Observatory.

an equal weight. To illustrate the difference in weight of values involved, Table 2 gives the data for the Washington–Madison and Washington–Ottawa connections.

How the results obtained with the Gulf pendulums agree with those obtained with the magnetically compensated Cambridge pendulums and the Brown pendulums is shown by the comparisons listed in Table 3. Although there are random differences of about one mgal in the various sets of data, these do not appear to be connected with any one set of apparatus, but seem to be common to all the pendulums. These variations are the ones referred to in the previous section for which there is no known explanation.

As the number of pendulum observations at each site are relatively few and the magnitude of these unexplained variations is appreciable (±1 mgal) it is questionable whether the final values adopted should be based on weighted averages of the pendulum data alone. It might be better to incorporate an adjustment based on gravimeter measurements as was done by the U. S. Coast and Geodetic Survey in determining the values for their 1950 gravity program. For the present this problem will have to be left in abeyance until all the pendulum results have been thoroughly studied and evaluated. The only additional field work now contemplated by the writers is the establishment of several sub-bases in the vicinity of each of the sites occupied. This appears to be desirable since most of the observations are at airports which are subject to constant constructional activity both in terms of renovation and expansion of facilities. By making gravimeter ties to two or more bench marks in the immediate vicinity of the airports from the present primary base, it will always be possible to effectively utilize the range even though the primary base may become lost or untenable because of new construction.

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Remanent Magnetization of the Upper-Miocene 'Blue' Sandstones of California

RICHARD R. DOELL

Abstract—A study has been made of the magnetization of some upper-Miocene sediments of California. Field evidence and laboratory experiments indicate that the main component of magnetization of these sediments was not acquired by alignment of detrital magnetic grains at the time of deposition, nor is it due to a later isothermal magnetization of these grains. A strong and stable magnetization appears to have developed through post-depositional and, in some cases, post-deformational growth of crystalline magnetic minerals *in situ*.

Introduction—Since this report is concerned with remanent magnetization of sedimentary rocks, it is desirable to discuss briefly how such rocks receive a remanent magnetization. *Nagata* [1953] has named the remanent magnetization that a rock possesses in the field 'natural remanent magnetization' (NRM). NRM is, in general, composed of two components, 'thermo-remanent magnetization' (TRM) and 'isothermal-remanent magnetization' (IRM). As will be proposed in this report, there may also be a third component, termed here 'crystallization magnetization.'

Magnetic minerals—essentially magnetite, hematite, maghemite, titanomagnetites, and some iron sulfides (likewise the rocks containing them)—acquire TRM by being heated above their Curie points and then cooling in a magnetic field, which may be relatively weak (of the order of the Earth's field, about 0.5 oe). IRM is, on the other hand, imparted to a rock at room temperature by the application of an external field (usually large); that is, the rock may show the well-known property of hysteresis. Both IRM and TRM are normally aligned in the direction of the field acting at the time they are imparted to the rock. It is apparent, then, that igneous rocks will acquire a TRM when they cool in the Earth's magnetic field. They may also, at a later date, acquire an IRM from lightning bolts, or possibly from the influence of the Earth's field acting over long periods of time.

Sedimentary rocks are, of course, formed from material primevally eroded from igneous rocks. Consequently, the magnetic mineral grains they contain may possess TRM or IRM which was originally imparted to the grain in the parent igneous rock, or both. During the process of sedimentation these grains may become statistically aligned in the Earth's magnetic field [*Clegg* and others, 1954; *Johnson* and others, 1948; *Nagata* and others, 1943] and thus give the sediment a remanent magnetization. Further, the sediment may acquire a component of IRM or crystallization magnetization after consolidation, or both.

Of further interest here are the properties of IRM and TRM. The principal difference between these two types of magnetization lies in their respective stabilities. TRM is but slightly changed by the application of many disturbing effects, and is destroyed only by heating the material to its Curie point. IRM is, on the other hand, considerably changed by the application of ac magnetic fields [*Matsusaki* and others, 1954] or by heating to relatively low temperatures.

Geologic setting—This report describes experiments performed on sandstones of uppermost-Miocene age occurring at three localities in the San Francisco Bay region of California. These rocks are very similar in lithology to the Etchegoin formation, occurring in the Great Valley of California. *Lynton* [1931] found some rather strong magnetic anomalies over the Kettleman Hills oil field which he attributed to the Etchegoin formation. Because of the apparently strong magnetic character of these sediments, they were selected for remanent magnetic studies.

Twelve oriented samples were taken from Corral Hollow, east of Livermore, California, in the summer of 1953. Subsequently, seven samples were collected in Bailey Canyon, just south of Pittsburg, California, and ten samples were taken from two localities east of Santa Cruz, California. The locations of these three areas are shown in Figure 1.

The beds in Corral Hollow, the Neroly formation [*Huey*, 1948], are folded into a rather steep syncline and anticline. A map showing the location of the samples taken here is given in Figure 2, with a geologic cross-section of these beds. Grain sizes of the sandstones vary from coarse (1–2 mm in diameter) to very fine siltstones, and some clays are present. Some of the rocks are well cemented with carbonates and others are practically devoid of cement. The most characteristic

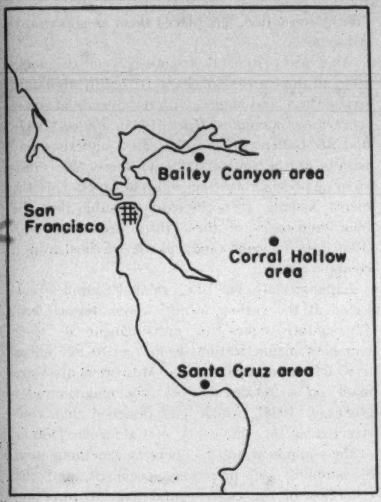

FIG. 1 – Location map

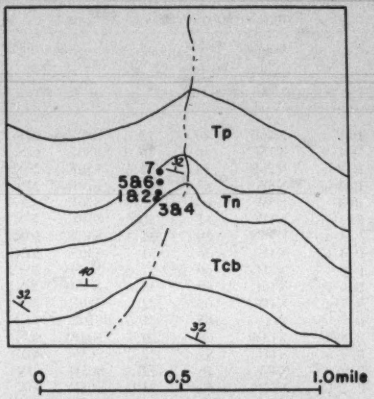

FIG. 3 – Sample locations at Bailey Canyon: Tp—Pinole Tuff; Tn—Neroly (undifferentiated); Tcb—Cierbo

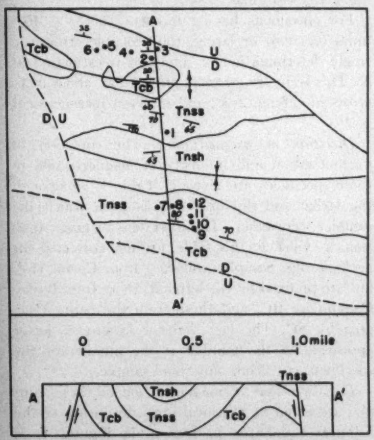

FIG. 2 – Sample locations at Corral Hollow: Tnsh—Upper Neroly (shales); Tnss—Lower Neroly (blue sandstones); Tcb—Cierbo (sandstone)

feature of these sandstones, as well as those from the other two localities, is a distinctive blue color seen in the hand specimen. The color is due to a very thin coating (0.007 mm average thickness) of translucent material which covers nearly all grains, but does not fill the interstices. The coating is colorless when seen in thin section, but when covering the dark grains in the rock, it gives rise to the distinctive blue color. J. Lerbeckmo (personal communication, 1955), on the basis of x-ray diffraction patterns and other tests, finds the coating to be an iron-rich clay material with a montmorillonite-type structure, although it was previously thought to be opal [*Patten*, 1947]. The age of the Neroly is given as uppermost-Miocene [*Huey*, 1948].

In Bailey Canyon, the Neroly also occurs in a section with other Tertiary sediments, all of which are dipping uniformly to the north at about 35°. The geologic map shown in Figure 3, with the sample locations, is taken from *Patten* [1947]. Lithology is practically identical with that at Corral Hollow.

In the Santa Cruz area the blue sandstones are flat-lying and apparently have been undisturbed since deposition. Six samples were taken near the eastern edge of Section 21, R.1 W., T.10 S., New Almaden Quadrangle, and four were taken in Section 14, R.1 W., T.10 S., New Almaden Quadrangle. The samples were taken from different stratigraphic horizons and were usually separated by a few hundred feet horizontally. The lithology is very similar to that of the Neroly sandstones, except for a general lack of cementing. On the basis of detrital mineral grain analyses, *McAndrews* [1948] has correlated these rocks with the

TABLE 1 – *Magnetization of specimens*

No.	Azimuth of magnetic axis	Inclination of magnetic axis (down)	Intensity of magnetization $\times 10^6$	Geologic attitude	
				Strike	Dip
	°	°	cgsu/cc	°	°
B–1–a	N16E	46	15.5	S80E	62S
B–1–b	N15E	46	16.0	S80E	62S
B–2–a	N26E	53	24.5	S50E	20N
B–3–a	N5W	67	36.3	S70E	27N
B–3–b	N5W	66	35.5	S70E	27N
B–3–c	N1W	65	36.0	S70E	27N
B–4–a	DueN	59	31.1	S40E	30N
B–4–b	N4E	56	31.3	S40E	30N
B–6–1	N21E	60	37.4	N45W	20N
B–6–2	N16E	60	38.6	N45W	20N
B–7–a	N4W	65	22.5	S70E	90
B–7–b	N6E	65	21.6	S70E	90
B–8–1	N13W	68	20.1	N60W	80N
B–9–a	N17E	81	22.2	S65E	80N
B–9–b	N4W	76	23.2	S65E	80N
B–10–a	N32E	58	33.0	S65E	80N
B–10–b	N22E	64	28.2	S65E	80N
B–10–c	N11E	61	21.1	S65E	80N
B–10–d	N27E	63	21.1	S65E	80N
B–10–e	N5W	66	27.8	S65E	80N
B–11–a	N10E	62	32.4	S65E	80N
B–11–b	N17E	66	31.3	S65E	80N
B–11–c	N15E	65	28.2	S65E	80N
B–12–1	N11E	62	35.3	N75W	78N
BC–1–1	N19E	56	13.0	N72W	35N
BC–1–2	N20E	52	12.6	N72W	35N
BC–2–1	N2E	55	5.46	N72W	35N
BC–2–2	N8E	59	5.60	N72W	35N
BC–2–3	N4W	56	6.92	N72W	35N
BC–3–1	DueN	60	17.8	N85W	36N
BC–3–2	N14E	66	19.0	N85W	36N
BC–4–1	N12E	55	18.5	N85W	36N
BC–4–2	N3W	56	15.5	N85W	36N
BC–5–1	N15E	55	30.8	E–W	21N
BC–5–2	N13E	55	29.1	E–W	21N
BC–6–a	N12W	58	5.98	E–W	21N
BC–7–a	N27E	61	6.64	E–W	29N
SC–1–1	N20E	50	15.5	N12W	8W
SC–1–2	N20E	57	10.7	N12W	8W
SC–1–3	N24E	58	9.57	N12W	8W
SC–3–1	N31W	70	8.20	N75E	18S
SC–5–1	N3W	57	8.22	Horizontal	
SC–5–2	N8E	73	7.70	Horizontal	
SC–5–3	N8W	63	8.62	Horizontal	
SC–6–1	S46W	44	8.46	Horizontal	
SC–6–2	S25W	45	8.98	Horizontal	
SC–7–1	N17E	52	7.60	Horizontal	
SC–7–2	N8E	60	9.82	Horizontal	
SC–7–3	N15E	62	9.60	Horizontal	
SC–8–1	N10E	57	3.03	Horizontal	
SC–8–2	N32E	57	2.68	Horizontal	
SC–8–3	N14E	53	2.74	Horizontal	
SC–9–1	N24W	48	2.37	Horizontal	
SC–9–2	N9E	31	3.58	Horizontal	
SC–9–3	N23W	43	2.95	Horizontal	
SC–9–4	N19W	36	2.67	Horizontal	
SC–10–1	N8W	55	5.76	Horizontal	
SC–10–2	N1W	54	5.95	Horizontal	

Neroly formation, and placed them as uppermost-Miocene.

The heavy mineral assemblages of the rocks from all three areas are characterized by abundant hypersthene and augite, with hornblende in somewhat lesser amounts. *Huey* [1948], *Patten* [1947], and *McAndrews* [1948] all suggest andesites and basalts as the source rocks for these blue sandstones, presumably the volcanic rocks of the Sierra Nevada. It is therefore probable that the blue sandstones of these three areas were deposited at the same time and were derived from a common source.

Experimental—The 29 oriented samples collected at the various localities were formed into 58 one-inch cubes for measurement of their remanent magnetization. From one to five cubes were cut from each sample. Measurements were made on a 'rock-generator' type magnetometer [*Johnson*, 1938], which was designed and constructed at the University of California. Details of the equipment and its operation, methods used in sampling and preparing specimens, and the reduction of the experimental data to direction and intensity of magnetization of the specimens are given elsewhere [*Doell*, 1955].

For specimens having moments of 5×10^{-5} units (cgs em) or larger, the probable error in a single determination of direction is estimated at 5°. This is due to errors in orientation, about 2–3°, errors in cubing, 2–3°, and errors in measurement of 2°.

Direction of magnetization—The direction of magnetization and intensity of magnetization of these specimens are given in Table 1, along with the strike and dip of the beds from which the samples were taken. The directions of magnetization, as given in this table, are not corrected for geologic dip. Samples collected from Corral Hollow are prefixed by the letter B, those from Bailey Canyon by BC, and those from the Santa Cruz area by SC. The last digit or lower-case letter appearing in the number is the number of the specimen cut from any one sample.

The directions of magnetization of these samples are given in graphical form, by means of the Schmidt equal-area projection, in Figures 4, 5, and 6 for the Corral Hollow, Bailey Canyon, and Santa Cruz areas, respectively. All of the directions of magnetization measured were north-seeking downward; thus, all points on the Schmidt projections are on the lower hemisphere.

Since these directions are not corrected for geologic dip, it is apparent that the magnetization was acquired after the beds were folded, that is,

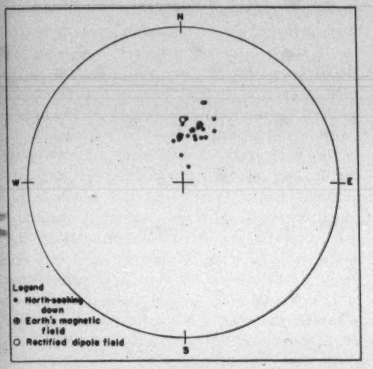

FIG. 4 – Directions of remanent magnetization at Corral Hollow

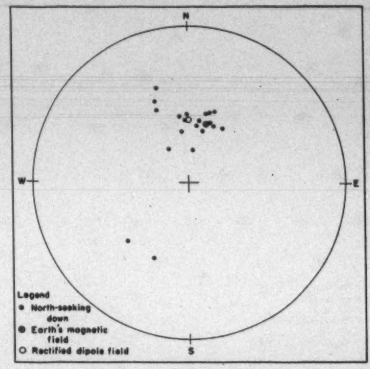

FIG. 6 – Directions of remanent magnetization at Santa Cruz

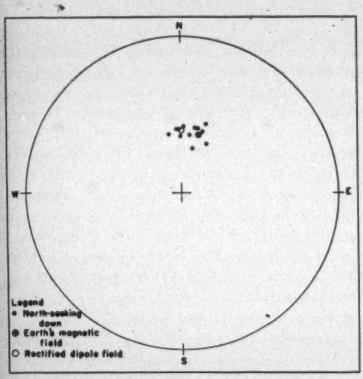

FIG. 5 – Directions of remanent magnetization at Bailey Canyon

for the Corral Hollow area (and also for the Bailey Canyon area, as will be pointed out later).

In measurements of the direction of magnetization of a number of specimens from some particular series of rocks, it is always of interest to determine the average direction of magnetization and the significance of this average direction. The statistical treatment of dispersion on a sphere [*Fisher*, 1953] is used for this test of significance. By this method, the average azimuth and inclination of the magnetic axes of the specimens are determined along with an 'angle of confidence,' θ. This is the semi-angle of a cone whose apex is at the geographical point in question and

TABLE 2 – *Average directions of magnetization and 'angles of confidence'*

Area	Azimuth E. of N.	Inclination	θ
	°	°	°
Corral Hollow.....	10½	63	3½
Bailey Canyon.....	8½	58½	3½
Santa Cruz.....	3	56	6½
All areas.....	7	58	2½

whose axis is the direction given by the average azimuth and inclination. For a 95-pct probability, the true direction of magnetization lies within this cone for 95 pct of such determinations. Any value of probability may be used, and 95 pct is used throughout this report. This treatment was applied to the data in Table 1 with the following results, shown in Table 2.

The two data from the Santa Cruz area in the SW quadrant (the two specimens cut from sample SC-6) were not used in this calculation. Apart from the possibility of misorientation (they are roughly 90° from the average direction), no reason can be given for this large discrepancy.

These results are shown in graphical form in Figure 7. Also indicated on the projection are the directions of the present geomagnetic field in the area, and of the rectified dipole field. The latter is that which would be due to a magnetic dipole situated at the center of the Earth and oriented along the axis of rotation from north to south. This is considered to be the average direction of the Earth's magnetic field when taken over a few thousand years [*Hospers*, 1955]. The average

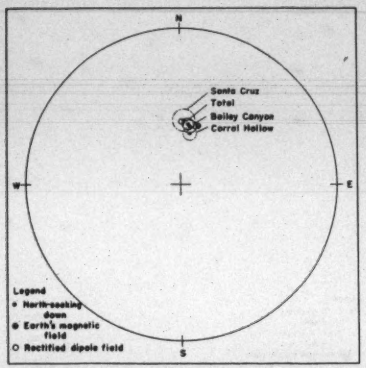

FIG. 7 – Average directions with 'circles of confidence'

directions calculated from the three separate areas are not significantly different from each other, but are significantly different from the Earth's present magnetic field, which in this area has a declination of 18° E and an inclination of 58°. The rectified dipole field is inclined at 57°.

The magnetization of the Corral Hollow rocks is obviously not that which they may have acquired at the time they were deposited. If the magnetization had been acquired during deposition, and had retained its original direction, then the subsequent folding should have considerably scattered the directions of the individual samples. In such a case, by correcting the directions of magnetization for geologic dip, that is, 'unfolding the beds,' this scatter would be decreased and the directions would all approach the average direction [*Graham*, 1949]. In the Corral Hollow rocks, the individual directions cluster about the average direction *in situ*, and correcting for geologic dip causes considerable scatter. Therefore, these rocks received a 'uniform' magnetization after they were folded. Further, the magnetization of the Corral Hollow rocks may not have been acquired over a period of time of several thousand years under the action of the Earth's field. This assumes that the field acting at the time these rocks received their magnetization had, on the average, the same direction as the rectified dipole field. *Hospers* [1955] concluded that this has been the case since the Oligocene.

The same conclusions can likewise be drawn from the measurements of the Bailey Canyon rocks, that is, that they received their magnetization after they were tilted, and that this magnetization may have been acquired during a relatively short period of time. The scatter in the data used by Hospers, however, does not completely exclude the possibility of slight long-term departures of the average field from the direction of the rectified dipole field since that time. The Bailey Canyon and Corral Hollow rocks probably received their magnetization only very recently, that is, after folding (lower Pleistocene). Thus, the magnetization of these rocks (if acquired over a period of several thousand years) may indicate a slight departure of the direction of the average field from that of the rectified dipole field during the lower Pleistocene. It may be, however, that these magnetizations are not stable over periods of time of the order of a few thousand years, and are, therefore, altered by the present field of the Earth.

The results for the Santa Cruz area are what might be expected for a stable magnetization that had been acquired at the time of deposition. Since the samples surely cover a period of deposition of at least several thousand years, the average direction of magnetization of such a group of samples should be that of the average field which existed during the period of deposition. There is, of course, no way of determining from the measurements of the directions of magnetization whether the magnetization of the Santa Cruz rocks is or is not completely stable. However, stability is indicated by the laboratory tests and the significant difference of the average direction from the direction of the geomagnetic field. Moreover, it is unlikely that these rocks owe their magnetization to an alignment of the detrital magnetic grains (see below).

It is worth noting that the period of deposition of these sediments (uppermost-Miocene) is a period for which reversals of the main geomagnetic field have been postulated [*Roche*, 1953]. Late Pliocene (possibly lower Pleistocene) sediments are folded with the Neroly, whereas middle Pleistocene sediments are not (C. M. Gilbert, personal communication, 1955). Thus the main period of folding occurred during the lower Pleistocene. This is also reported as a period of reversals [*Hospers*, 1955]. Although the Neroly sediments apparently no longer reflect the direction of the geomagnetic field at the time of their deposition (if they ever did), it is thought that they were magnetized under the action of the Earth's field during the later phases of deformation or just after deformation (that is, lower Pleistocene). All of the rocks reported here are 'normally' magnetized.

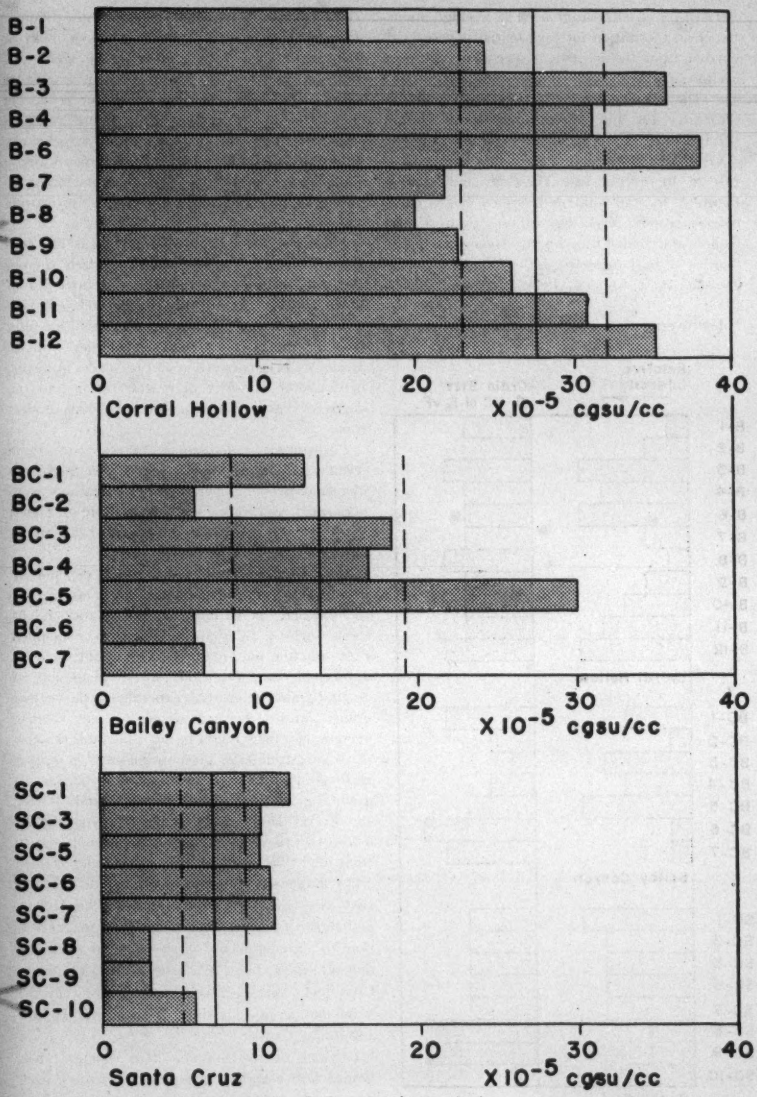

FIG. 8 – Intensity of magnetization

Intensity of magnetization—The average intensity of magnetization for each of the samples, calculated from the individual specimens cut from each sample, is shown in Figure 8 in units of 10^{-5} cgs. The average magnetizations with probable errors for the three areas are: Corral Hollow (27.5 ± 4.6) $\times 10^{-5}$ units, cgs; Bailey Canyon (13.8 ± 5.5) $\times 10^{-5}$ units, cgs; Santa Cruz (7.2 ± 2.0) $\times 10^{-5}$ units, cgs. These are indicated in Figure 8 by the solid and dashed lines. These magnetizations, especially those from Corral Hollow and Bailey Canyon, are somewhat higher than is usually reported for sedimentary rocks [*Nagata*, 1953; *Graham*, 1949; *Clegg* and others, 1954].

The average intensity of magnetization of the rocks from Corral Hollow is significantly different from that of either the Bailey Canyon rocks or the Santa Cruz rocks. There is no significant difference between the Bailey Canyon and Santa Cruz areas, although a tendency for a weaker magnetization from the Santa Cruz rocks is apparent. This lack of significance is primarily caused by the large scatter of the Bailey Canyon data, and it is possible that the two might be shown to be significantly different by measuring more samples.

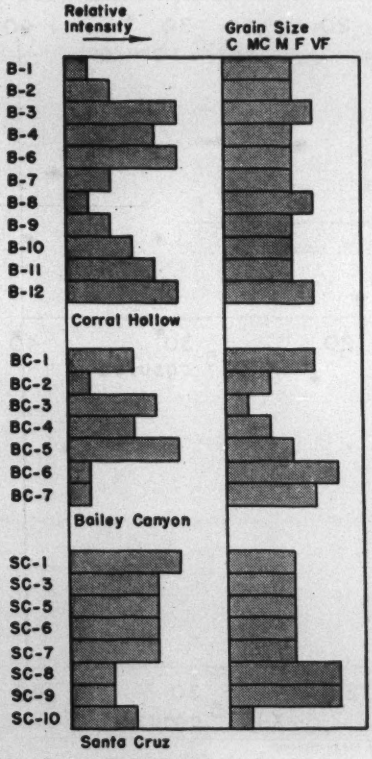

FIG. 9 - Grain size and relative intensity

Since the rocks from all three areas are considered to be contemporaneous and derived from the same source, the difference in intensity of magnetization is probably not correlated with differences in general lithology. This is especially true for the Corral Hollow and Bailey Canyon areas. A direct correlation can be made, however, between the intensity of magnetization and the degree of diastrophism that the rocks have undergone.

Petrographic examination—In view of these results, the samples were studied under the binocular microscope, mineral grain separations were performed, and some rock sections were examined in an attempt to explain the observed differences in magnetization.

Since *Graham* [1949] had found a dependence of intensity of magnetization on grain size, it was thought that the flat-lying Santa Cruz rocks might show such a relationship. Graham concluded that only the finer-grained rocks would show an appreciable magnetization due to alignment of detrital grains, since in his experiments the coarser grains did not become aligned to any degree, even though there might be a considerable amount of magnetic material present. Figure 9 compares relative intensity of magnetization with relative grain size for the Santa Cruz rocks (and also for the Corral Hollow and Bailey Canyon rocks). The correlation here seems to be just opposite to what might be expected, that is, the finer-grained rocks show weaker magnetizations. This indicates that these rocks, like those from Corral Hollow and Bailey Canyon, do not owe their magnetization to an alignment of the detrital magnetic mineral grains. Thus, it is assumed that the Santa Cruz rocks received their magnetization in the same manner as did those from Corral Hollow and Bailey Canyon.

Portions of the samples were disaggregated, formed into composite samples representing each area, washed in acidic and basic solutions (the basic solution was required in order to remove the

thin clay coating) and separated into light and heavy fractions by use of bromoform [*Milner*, 1940]. The 'magnetic' grains were then removed from the heavy fraction by the use of a small hand magnet. Examination of these grains under the binocular microscope reveals that most of them are about 0.1 to 0.5 mm in diameter, and are composed of a glassy material containing inclusions of an opaque material, presumably magnetite or a related mineral. The opaque material constitutes up to 50 pct of the grain in a few cases, but normally forms a much smaller portion of the grain. Smaller opaque grains, averaging about 0.05 mm in diameter, are also present in lesser amounts (perhaps two to three per cent of the total 'magnetic' grains). Most of this material shows effects of transport and is undoubtedly derived from the volcanic source rocks. It is extremely unlikely that such grains would receive a statistical alignment in the Earth's field. Further, there is no observable difference in the 'magnetic' grains from the different areas.

X-ray powder diffraction patterns were made from this material identifying it as magnetite having a cell dimension of about 8.40 A. There is no significant difference in the lattice dimensions of grains from the different areas.

Spectrochemical determinations were also made on this material, to test for differences between the areas. The results of these determinations, which were carried out by G. M. Gordon at the Division of Mineral Technology, University of California, Berkeley, California, as tests number 629-55 and 616-55 are shown in Table 3. Small amounts of *V*, *Cr*, *CaO*, *MgO*, etc., are also present in all samples. From these tests it is concluded that the detrital magnetic mineral grains of the three areas are made up of the same material.

Although the character of the 'magnetic' grains makes it difficult to determine relative percentages of magnetite from the rocks at the various localities, there appear to be only slight differences. Thus, the differences in intensity of magnetization of the three areas are apparently not correlated with differences in the detrital magnetic mineral grains.

Chemical activity—There is, in all these rocks, an indication of post-depositional chemical activity involving iron. The deposition of the iron-rich clay coating on the grains indicates the previous presence of iron-rich solutions. Serrated edges on many hypersthene grains indicate solution of these minerals and therefore a liberation of some iron. It was noted, however, that the etching of the hypersthene grains occurred after deposition of the iron-rich clay coating. In some thin sections of the Neroly formation (obtained from J. Lerbeckmo) an opaque material is observed that fills or partially fills some of the inter-

TABLE 3 – *Results of spectrochemical analyses*

Sample	SiO_2	TiO_2	Al_2O_3	Mn
	pct	pct	pct	pct
B	10	1.0	1.0	0.1
BC	5	1.2	1.0	0.1
SC	10	1.2	1.0	0.2

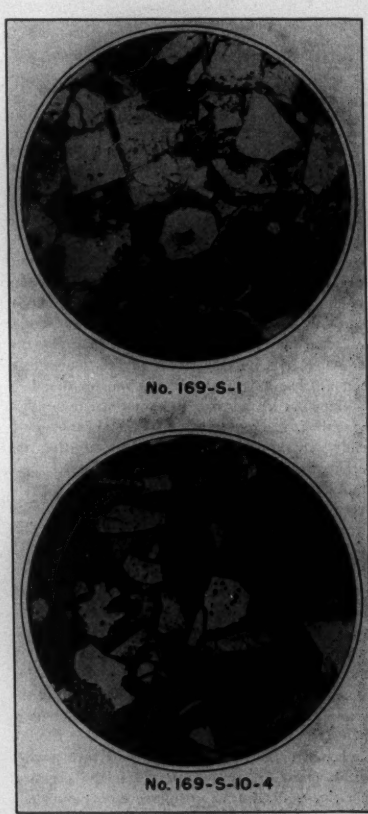

FIG. 10 – Photomicrographs of the Neroly sandstone; ordinary light, ×29 (Department of Geology Collection, University of California)

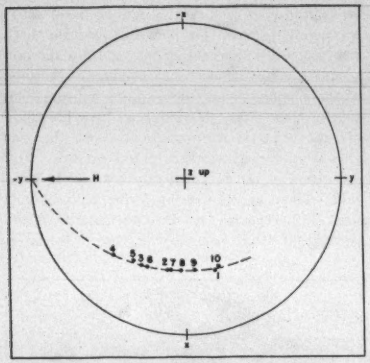

FIG. 11 – Treatment of specimen B-6-2: 1, repeat measurement; 2, 6 oe field, 15 min; 3, 6 oe field, 2 hr; 4, 6 oe field, 18 hr; 5, after 15 min recovery; 6, after 1 hr recovery; 7, after 8 hr recovery; 8, after 24 hr recovery; 9, 10 oe ac field, 30 min; 10, heated to 100°C and cooled in H = 0

stices (see Figure 10, which also clearly shows the clay coating). Some of this material appears reddish-brown along the edges, indicating that it may be limonitic or hematitic in character, and almost certainly a mineral rich in iron. Examination under reflected light and a high-powered binocular microscope indicates that some of this material, if not all, has a very fine crystalline texture. Lerbeckmo, in his personal communication in 1955, stated that the thin clay coating characteristically shows a dark rim on the side away from the grain. Because of the relatively high relief (high refractive index) of this rim, he suggests that it is very rich in iron and may quite possibly be an iron-oxide mineral.

This chemical action (deposition of the dark rims on the clay coating and filling of some interstices) might be expected to be more pronounced in the porous rocks, that is the coarser grained ones. There could also be a direct correlation with diastrophic activity, since, in general, more tightly folded rocks show greater alteration than do undisturbed sediments. Because of the crude correlation of increased intensity of magnetization with increase in grain size, that is, with increased permeability (Fig. 9) and with greater diastrophism, it is suggested that the chemical activity has had a major influence on the magnetization of these rocks, and that the detrital grains contribute but little to the total magnetization.

Effects of heat and applied fields—It is known that some rocks may possess a soft component of magnetization [*Clegg* and others, 1955; *Graham*, 1954]. This magnetization is imparted to the rock by the action of an applied unidirectional magnetic field, and is, therefore, isothermal-remanent magnetization. The possibility exists that the magnetization measured in the blue sandstones is of this type and that it was induced in these rocks by the action of the Earth's magnetic field. If this were so, then it might be expected to have the properties of IRM, in particular, a linear decrease of intensity of magnetization with temperature [*Neel*, 1955] and not a 'Curie law' decrease. A linear decrease of magnetization is not, of course, restricted to IRM, since the TRM of some spinels decreases linearly with temperature.

Specimens B-6-2, BC-5-2, and SC-1-3 were placed in dc magnetic fields of 6 oe directed along one of the cube edges in each case, and the resultant total magnetization measured after varying periods of time. The specimens were then removed from the field and the decay of this isothermal magnetization was measured. Figures 11, 12, and 13 show the effect of this treatment on the direction of total magnetization. Since the direction of magnetization in all these experiments follows a great circle containing the original direction of magnetization and the direction of the applied field, it is apparent that the components of magnetization normal to the applied field were not affected by the treatment. Further,

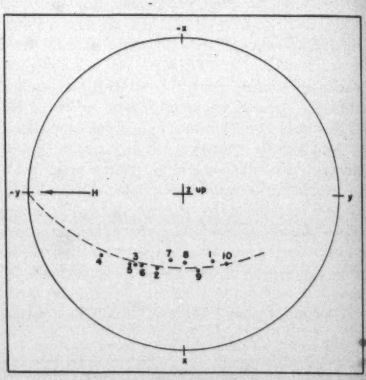

FIG. 12 – Treatment of specimen BC-5-2: 1, repeat measurement; 2, 6 oe field, 15 min; 3, 6 oe field, 1¼ hr; 4, 6 oe field, 18 hr; 5, after 15 min recovery; 6, after 1 hr recovery; 7, after 8 hr recovery; 8, after 24 hr recovery; 9, 10 oe field, 30 min (ac); 10, heated to 100°C and cooled in H = 0

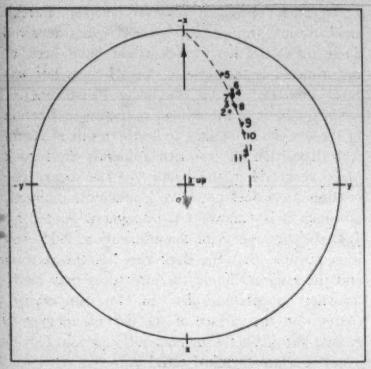

FIG. 13 – Treatment of specimen SC-1-3: 1, repeat measurement; 2, 6 oe field, 15 min; 3, 6 oe field, 45 min; 4, 6 oe field, 2 hr; 5, 6 oe field, 19 hr; 6, after 15 min recovery; 7, after 1 hr recovery; 8, after 5 hr recovery; 9, after 26 hr recovery; 10, 10 oe ac field, 30 min; 11, heated to 100°C and cooled in H = 0

after a period of relaxation of 24 hours or more, a component of isothermal magnetization remained in the direction of the applied field. This component could then be partially removed by the application of an ac magnetic field (about 15 oe) and completely removed by heating the specimen to 100°C and cooling it in a field of zero intensity. Presumably a longer application of the ac field would completely remove this isothermal magnetization also.

Several of the remaining specimens were then remeasured, heated to 100°C and cooled in zero magnetic field and measured again. A few were then heated to 200°C and cooled in zero magnetic field and again remeasured. Table 4 gives a tabulation of the intensities of magnetization determined by these measurements.

Although several of the samples increased their magnetization after heating to 100°C the general trend seems to be a decrease. To ascertain whether this decrease at 100°C is significant, the data were converted to percentage loss in magnetization, and the average decrease and probable error of this decrease were computed. The result is an average decrease in magnetization of 9½ pct. However, the probable error is 13½ pct; thus, this decrease in magnetization has no significance and is ascribed to random causes. The average loss after heating to 200°C and cooling in zero applied field is 62 pct with a probable error of 9 pct.

The test of dispersion on a sphere by *Fisher* [1953] was also applied to the directions both before and after heating to 100°C. The measure of confidence, θ, was 5½° before treatment and decreased to 4½° after heating. There is no significant difference in the average direction of magnetization between measurements before and after heating to 100°C. This is a further indication that the magnetization removed by the 100°C heat treatment was of a random nature. From these tests it is concluded that the principal

TABLE 4 – *Effects of heating*

No.	Repeat measurement (× 10⁶)	Heated to 100°C; cooled in H = 0 (× 10⁶)	Heated to 200°C; cooled in H = 0 (× 10⁶)
	cgsu/cc	cgsu/cc	cgsu/cc
B-1-a	9.56	11.4	...
B-2-a	24.5	22.0	...
B-3-a	39.3	39.6	22.6
B-3-c	36.6	32.7	...
B-4-a	29.7	25.0	...
B-5-1	34.4	34.9	19.6
(not included above because of lack of orientation)			
B-6-1	37.4	28.0	...
B-7-a	22.5	18.3	...
B-7-b	21.6	19.2	...
B-8-1	18.1	23.0	...
B-9-a	21.8	19.9	...
B-9-b	23.2	17.4	...
B-10-c	21.1	19.8	10.7
B-10-d	21.1	21.3	5.9
B-11-b	30.6	28.9	...
B-11-c	28.2	22.9	8.96
B-12-1	35.1	23.3	10.9
BC-1-1	13.0	8.9	4.4
BC-1-2	12.9	10.0	...
BC-2-1	5.4	4.0	...
BC-2-2	7.6	4.4	...
BC-3-1	18.2	15.7	...
BC-3-2	18.7	17.4	...
BC-4-1	18.2	14.5	...
BC-4-2	18.5	13.3	...
BC-5-1	30.6	27.6	...
BC-5-2	29.6	27.6	...
BC-6-a	6.5	5.7	...
BC-7-b	13.8	12.4	2.4
SC-1-1	14.8	13.0	...
SC-1-2	11.2	9.2	...
SC-3-1	8.2	9.3	...
SC-5-1	7.6	7.0	...
SC-5-2	8.2	6.8	...
SC-6-2	3.4	5.3	...
SC-7-1	4.2	5.0	...
SC-7-2	9.7	7.4	...
SC-8-1	2.7	2.4	...
SC-8-2	2.3	2.9	...
SC-9-2	3.0	1.6	...
SC-10-1	7.2	6.1	...
SC-10-2	7.1	6.0	...

magnetization of these sediments is not of an isothermal type.

All the samples heated to 200°C showed marked chemical changes after this treatment. In particular, a thick brown coating formed on the surface of the originally light blue rocks and within the specimens the color had changed to a dark grey. The result was the same whether the rocks were heated in air or in an atmosphere of oil-free helium. The inference here is that the loss in magnetization is directly connected with these chemical changes. If the magnetization of these rocks had been caused by an isothermal magnetization of the detrital magnetite grains, a linear decrease with temperature should be observed instead of the marked decrease between 100° and 200°C. If the magnetization were caused by a TRM of the detrital magnetite grains, it should not be decreased appreciably at such a low temperature, since magnetites low in titanium have Curie points above 500°C [*Pouillard*, 1950]. It is possible that the detrital magnetite grains may be oxidized by the 200°C treatment. However, *Ovchinnokov* [1953], found that magnetite is stable to 220°C in an atmosphere of oxygen, which is a more oxidizing environment than that in which these sediments were heated, and that it transforms to maghemite between 220° and 260°C and goes directly to hematite above 260°C. It is therefore unreasonable to expect a chemical change of this nature to take place in the detrital magnetite grains during the heating experiments.

Conclusions—These studies seem to indicate several major points of interest:

(1) The magnetization of the rocks studied in this report is not, in the main, caused by either an alignment of the thermo-remanent magnetization or an isothermal-remanent magnetization of the detrital magnetite grains.

(2) This is a clear case of a stable magnetization in sediments that was acquired after folding and not at the time of deposition.

(3) This magnetization is not an isothermal magnetization in the usual sense, because: (a) it does not decrease linearly with temperature; (b) isothermal magnetization can be induced in these rocks and subsequently removed without affecting the original magnetization.

(4) A direct correlation may be made between the intensity of magnetization of the rocks and post-depositional chemical activity, which involves iron.

(5) A magnetization acquired as a result of chemical changes appears to have stability.

(6) There were no reversals of the Earth's field during the period(s) these rocks received their magnetization (which could have been at any time since the close of the Miocene, but was most probably during the lower Pleistocene).

On the basis of this evidence, the magnetization of these rocks is thought to be the result of chemical deposition of iron-rich minerals that took place very late in the history of the rocks. The coating itself does not have a magnetic moment, although it is somewhat paramagnetic (noted by J. Lerbeckmo, personal communication, 1955) but it is possible that the dark rims on the coating and the material filling the interstices may have. Another possibility lies in low-temperature changes on the surface of the detrital magnetite grains, but again the magnetization would be the result of a late chemical activity.

For lack of any evidence to the contrary, it seems reasonable to expect a magnetization obtained by chemical deposition (or crystal growth) to be oriented in the direction of the field acting at the time of deposition. 'Crystallization magnetization' is the name suggested for this phenomenon, which may be summarized as follows. A crystal growing or crystallizing in a weak magnetic field may acquire a magnetization that is more intense and more stable than the magnetization this same crystal (originally unmagnetized) would acquire if it were placed when fully grown in a field of the same intensity at the same temperature. There is no known experimental evidence to confirm this. If the crystals do not grow to a size large enough to consist of more than one domain (which is probably the case for the rocks studied here), the direction of magnetization of this domain might be expected to be in the direction of the applied field. A single-domain grain might also automatically develop with its direction of easy magnetization parallel to the applied field, since this orientation would require much less energy than would be needed later to turn the magnetization of such a single-domain grain against the anisotropy energy. Further, if the grains become larger than those consisting of one domain, it seems reasonable to expect an easier displacement of the domain boundaries while the crystal is growing than after it is fully grown.

To what extent this process takes place in other rocks is not known. However, the possibility should not be excluded, especially if the rocks in question come from a folded region or show evidence of a post-depositional chemical activity.

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Some Comments on the Deacon Wind Profile

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Abstract—Low-level wind profiles measured during Project Great Plains were used in the determination of z_0, the roughness parameter, and β, the parameter related to profile curvature in Deacon's formula. Anemometers were geometrically spaced at five levels between 40 and 640 cm. The z_0 values, one for each observation period, found from the four lowest anemometers exceeded the z_0 values found from the four highest anemometers. The β values computed from the highest anemometers departed more from unity than did the β values computed from the lowest set. Since the apparent variability of β with height may be due entirely to the variability of z_0, another analysis was conducted with the z_0 value fixed for all levels and all hours of an observation period. Although the β variation was reduced by this technique, the departure of β from unity continued to increase with height.

Since the Calder-Deacon solutions of equations of diffusion from continuous point and infinite line sources are functions of β and z_0 the effects of the height variation of β and z_0 on predictions of ground-level concentration were examined. The effects were found to be significant. When for each observation period, β was plotted against a modified form of the Richardson Number, the fitted curves did not coincide. There are indications that during inversion conditions the greatest departures from $\beta = 1$ occurred on nights characterized by the presence of a well-defined low-level wind maximum.

Introduction—For some time the vertical profile of mean wind speed has been a subject of interest to micrometeorologists. To those concerned with the problem of eddy diffusion of momentum and matter in steady-state conditions, the profile has become particularly important in recent years. Diffusion equations which vary in form and in boundary conditions have been studied, the solutions in many cases being functions of parameters which characterize the vertical profile of mean wind speed. For these solutions to be of value, it is necessary that the profile parameters be determinable and unique in a sense to be discussed later.

One form of the wind profile which has been widely used is that given by *Deacon* [1949]. In his analysis of an extensive series of wind and temperature measurements below a height of eight meters, Deacon found that an expression of the form

$$\frac{du}{dz} = \alpha z^{-\beta} \tag{1}$$

fitted the data well over a wide range of stability conditions. In this expression du/dz is the vertical gradient of mean wind speed, α and β are independent of the height z, and β, which reflects the degree of curvature of the wind speed profiles, has the values

$\beta > 1$ for negative (unstable) values of the Richardson number;

$\beta = 1$ for zero values of the Richardson number;

$\beta < 1$ for positive (stable) values of the Richardson number.

With the boundary condition $u = o$ at $z = z_0$, where z_0 is the roughness parameter, Deacon's generalized profile has the form

$$u = \frac{u_*}{k(1-\beta)}\left[\left(\frac{z}{z_0}\right)^{1-\beta} - 1\right] \tag{2}$$

Here u_* is the friction velocity and k is von Karman's constant. In the neutral case ($\beta = 1$), (2) becomes the logarithmic form

$$u = \frac{u_*}{k} \ln \frac{z}{z_0} \tag{3}$$

The values of the wind profile parameters u_*, β, and z_0 which are computed from (2) and a set of meteorological observations depend upon the actual method of analysis chosen. In a sense, then, the method of analysis defines the parameters.

From the most general point of view, u_*, β, and z_0 would be allowed to vary with height and stability. However, in the Deacon derivation of (2) from the empirical form (1) and in the Deacon method of computation all three of these parameters are assumed to be independent of height. In the Deacon approach to the computation of these parameters, z_0 is made independent of stability by taking it to be the value of the roughness parameter which satisfies (3). Thus, a method of analysis is fixed.

Employing this method, Deacon found z_0 from

a ratio of wind speeds at two heights during neutral conditions.

$$\frac{u_2}{u_1} = \frac{\ln (z_2/z_0)}{\ln (z_1/z_0)}$$

The values of β, varying with stability, were then obtained from the general form

$$\frac{u_2}{u_1} = \frac{(z_2/z_0)^{1-\beta} - 1}{(z_1/z_0)^{1-\beta} - 1}$$

Deacon found that, over short grass, values of β obtained from the ratios $u_{4m}:u_{1m}$ were generally closer to unity than those giving the best fit to the whole profile between a half and eight meters. Deacon offered two explanations for this apparent variation of β with height. First, he recognized the possibility that the departure of β from unity with an increase of height is real. Then, referring to unstable conditions, he added:

> "There is also some reason to suppose that a part of this increase of β with height may be due to the incursion of large eddies from the surrounding rougher downland to the 200 yd square prepared area."

One purpose of this paper is to examine the variation with height of z_0 and β. A second purpose is to show how the height variations of z_0 and β affect predictions of ground-level concentrations downwind of continuous point and infinite line sources. A third purpose is to discuss the relationship between β and a modified form of the Richardson number.

Source of data—The low-level measurements used in this study were made in the summer of 1953 by research teams from a number of American universities and government agencies participating in Project Great Plains, a research program organized and directed by the Geophysics Research Directorate of the Air Force Cambridge Research Center [*Davidson* and *Lettau*, 1953]. The field site was a half-mile square of very level terrain about six miles east of O'Neill, Nebraska. The site had a fairly uniform cover of prairie grasses and was free of trees and shrubs. The adjoining lands, which were only slightly rolling, had a similar grass cover and were almost devoid of trees and shrubs.

During all of the observation hours employed in this study, the mean wind directions were within 50° of south. In contrast to an upwind fetch of about 190 yards in the Porton data used by Deacon, the upwind fetch at O'Neill consisted of about 500 yd of level terrain and uniform vegetation.

The low-level wind speed and temperature observations used in this study were those made by a group from the *Johns Hopkins University* [1953, 1954]. The speeds were measured with modified Friez three-cup anemometers. The instruments had been calibrated in the Bureau of Standards wind tunnel one month before the commencement of the field program. Before an observation period began, nine anemometers, previously selected for comparability, were mounted on a horizontal bar in the natural wind. The five anemometers which agreed most closely were installed on the mast at heights of 40, 80, 160, 320, and 640 cm. For these heights, only hourly means of wind speed were employed in this study.

Air temperatures were measured with shielded copper-constantan thermocouples at seven heights between 10 and 640 cm above ground. The reported temperatures are mean values of 20 observations at each level, all taken during a five-minute period centered at 35 minutes past the hour.

Determination of z_0 and β—The method of analysis employed here is with minor modifications the one suggested by *Deacon* [1949, 1953] and employed by others [*Lake*, 1952; *Pasquill*, 1949; *Rider*, 1951, 1953]. In this method a value of z_0, the roughness parameter, is obtained in neutral conditions and employed throughout the observation period. In this study the shortest observation period was 21 hours, the longest 48 hours. A wind ratio, R, was defined as follows:

$$R = \frac{u_4 + u_3 - (u_2 + u_1)}{u_4 + u_3 + u_2 + u_1} \tag{4}$$

In general, R is a function of z_0, β, and z.

A stability ratio, Ri', roughly proportional to the Richardson number, was defined as follows

$$Ri' = \frac{T_{640} - T_{10}}{u_{240}^2} \tag{5}$$

where T_{640} and T_{10} are the mean temperatures at heights of 640 and 10 cm and u_{240} is the mean wind speed at 240 cm. (In order to retain an Ri' form used in an earlier study, u_{240}, found by interpolation, was employed.) The neutral or adiabatic condition is assumed to occur when the stability ratio is zero.

Values of R were computed for each hour of an observation period. These values were plotted against the stability ratio; a free-hand curve was drawn to fit the data. The adiabatic value of R, denoted as R_{ad}, was determined from the intersection of this curve with the line $Ri' = 0$. A

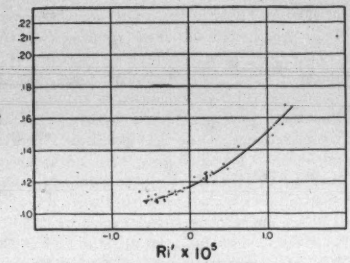

FIG. 1 – Variation of R with stability ratio, August 24–25, 1953

sample determination of R_{ad} is given in Figure 1. Application of the logarithmic profile for adiabatic conditions gives

$$R_{ad} = \frac{\log z_4 + \log z_3 - (\log z_2 + \log z_1)}{\log z_4 + \log z_3 + \log z_2 + \log z_1} \quad (6)$$

from which z_0 was computed. It will be noted that this method gives but one value of z_0 for an entire observation period. With this value of z_0 and the hourly values of R, hourly values of β were found from (2) and (4). Although, in this procedure, wind data from only four levels are required to find z_0 and a set of β values, wind data from five levels were available at O'Neill. Thus z_0 and β are 'over-determined' in the sense that more than one set of z_0 and β values can be obtained. Actually, two sets of z_0 and β values were found, one set from the four anemometers nearest the ground and the other set from the four anemometers furthest from the ground. Values of z_0 determined from the four lowest anemometers are denoted as $z_{0,L}$ while those determined from the four highest anemometers are denoted as $z_{0,H}$. The values of z_0 are given in Table 1. It is to be noted that the prairie grass was given a rough mowing prior to August 1 and a smooth mowing on August 12. The second mowing cut the grass at a height of approximately six cm, and accounted for the decrease in z_0 between the first and second observation periods. The $z_{0,L}$ values consistently exceed the $z_{0,H}$ values.

TABLE 1 – *Values of z_0 at O'Neill, Nebraska, August to September 1953*

Observation period	$z_{0,H}$	$z_{0,L}$
	cm	cm
Aug. 8–9	0.92	1.3
Aug. 13–14[a]	0.55	0.67
Aug. 18–19	0.55	0.77
Aug. 22–23	0.61	0.95
Aug. 24–25	0.61	0.86
Aug. 28	0.64	0.77
Aug. 31–Sept. 1	0.64	0.80
Sept. 7–8	0.64	0.80

[a] Grass mowed on August 12

When the β values obtained from the upper set of anemometers (β_H) were compared with the corresponding β values obtained from the lower set of anemometers (β_L) for all hours of the eight observation periods studied, it was found that the β_H values generally departed more from unity than did the β_L values. Table 2, which contains the bivariate frequency distribution of β_H and β_L, illustrates this variation of β with height. Were there no variation with height, the entries in Table 2 would tend to lie along or be scattered symmetrically about the diagonal line shown in the table. It can be seen, however, that for β_L values less than 0.99 there is a strong tendency for β_H values to be less than the corresponding β_L values. In the β_L region 1.02 to 1.07 there is a slight tendency for β_H values to be greater than the corresponding β_L values.

However, in spite of the fact that β seems to vary with height, it appears possible that part or all of this variation of β with height is the result of the variation of z_0 with height. Therefore, in a second analysis, z_0, chosen to be approximately a mean value for the mast as a whole, was determined for each observation period. The appropriate mean value of z_0 was taken to be that found from R defined as the ratio of the mean wind speed at 320 cm to that at 40 cm. Figure 2 illustrates the method used in finding three sets of β for each observation period. Note that while the earlier analysis was conducted with a four-level form for R, the present analysis was done with a two-level form, similar in this respect to the one employed by *Deacon* [1949, 1953].

This analysis gives three sets of β for each observation period. Bivariate frequency distributions of β_1 and β_2, β_1 and β_3, and β_2 and β_3, are given in Tables 3, 4, and 5. It can be seen again that β decreases with height during inversion conditions and shows a slight tendency to increase with height during lapse conditions. Therefore, in spite of the use of a single value of z_0 for each observation period, a variation of β with height is again indicated.

Since the values of z_0 obtained in the manner described above decrease with height, there are

TABLE 2 – *Bivariate frequency distribution of β_H and β_L*

β_H	β_L											
	0.72–0.74	0.75–0.77	0.78–0.80	0.81–0.83	0.84–0.86	0.87–0.89	0.90–0.92	0.93–0.95	0.96–0.98	0.99–1.01	1.02–1.04	1.05–1.07
1.05–1.07											5	1
1.02–1.04										14	36	1
0.99–1.01										34	9	
0.96–0.98									32	17		
0.93–0.95									7	2		
0.90–0.92								10	3			
0.87–0.89							1	7				
0.84–0.86							3	2				
0.81–0.83					1	1	2					
0.78–0.80						3						
0.75–0.77					1	1						
0.72–0.74				1	3							
0.69–0.71			1									
0.66–0.68			1	1								
0.63–0.65	2											
0.60–0.62	3											

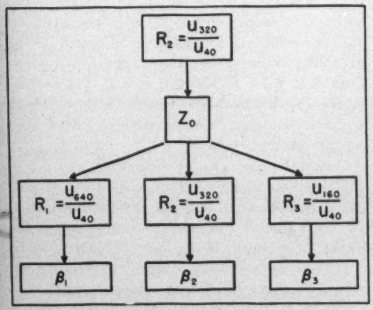

FIG. 2 – Second method of determining β

good indications that for the conditions found at O'Neill the logarithmic law is not strictly applicable in the lowest 640 cm during neutral conditions. The same method of analysis shows that β is variable with height in this layer at O'Neill. The variation of β is in the same direction as that found by Deacon. At O'Neill, however, there is a long upwind fetch of uniform terrain and vegetative cover. Therefore, the variation of β with height cannot be ascribed to an 'incursion of eddies' from surrounding rougher surfaces, an explanation offered by Deacon for the β behavior at Porton, England.

Effects of z_0 and β variations on computed concentrations at ground level—In view of the z_0 and β variations found in the chosen method of analy-

TABLE 3 – *Bivariate frequency distribution of β_1 and β_2*

β_1	β_2											
	0.72–0.74	0.75–0.77	0.78–0.80	0.81–0.83	0.84–0.86	0.87–0.89	0.90–0.92	0.93–0.95	0.96–0.98	0.99–1.01	1.02–1.04	1.05–1.07
1.08–1.10												1
1.05–1.07											13	1
1.02–1.04										32	39	
0.99–1.01									8	39		
0.96–0.98									33	1		
0.93–0.95								6	10	1		
0.90–0.92							3	7				
0.87–0.89							1	2				
0.84–0.86						6	3					
0.81–0.83						2						
0.78–0.80					2							
0.75–0.77				2								
0.72–0.74		1		1								
0.69–0.71	1		1									
0.66–0.68	1											

sis, it appeared worthwhile to determine what effects these variations have on the values of ground-level concentration computed from the Calder-Deacon solutions of the basic diffusion equations for continuous sources [*Deacon*, 1949] (also memorandum from K. L. Calder entitled A theoretical treatment of the problem of the diffusion of matter in the lowest layers of the atmosphere from a point source, about 1949). These solutions, which allow for variability of wind speed and eddy diffusivity with height, are expressed as functions of, among other parameters, both β and z_0. The following question is to be answered: If one analyst chooses to use wind data from the top four anemometers, how do his predictions of concentration downwind of continuous point and infinite line sources differ from those made by another analyst who chooses to use wind data from the bottom four anemometers?

In the attempt to answer this question, three stability conditions were considered, the strong inversion, the moderate inversion, and the strong lapse. For each condition an appropriate wind speed at a height of two meters and a pair of β_H, β_L values which Table 2 indicated to be plausible were assumed. These appear in the first column of Table 6. The $z_{0,H}$ and $z_{0,L}$ values used in the computations are those of August 18–19 and are somewhat representative of mid-August roughness parameters.

Concentrations (χ) were determined at a downwind distance of 100 m. Two concentrations were calculated, one from $(z_0, \beta)_H$ and the other from $(z_0, \beta)_L$. In each case, the ratio of χ_H to χ_L was found. The results are shown in Table 6.

It can be seen that during moderately to strongly stable conditions the concentrations computed by the two analysts may differ by factors of 3 to 5 at a distance of 100 m from a continuous point source and factors of 2 to 3 from a con-

TABLE 4 – *Bivariate frequency distribution of β_1 and β_3*

β_1	β_3											
	0.72–0.74	0.75–0.77	0.78–0.80	0.81–0.83	0.84–0.86	0.87–0.89	0.90–0.92	0.93–0.95	0.96–0.98	0.99–1.01	1.02–1.04	1.05–1.07
1.08–1.10											1	1
1.05–1.07										4	8	1
1.02–1.04										65	9	
0.99–1.01									16	33		
0.96–0.98								3	26	5		
0.93–0.95								2	16	1		
0.90–0.92							1	6	4	1		
0.87–0.89								2	1			
0.84–0.86							3	6				
0.81–0.83							1	1				
0.78–0.80						1	1					
0.75–0.77					1	1						
0.72–0.74			1		1							
0.69–0.71			1		1							
0.66–0.68		1										

tinuous infinite line source. During unstable conditions, the concentrations computed by the two analysts may differ by a factor of 2 at the same distance and for the same source types.

Relationship of β to Ri'—The variations of z_0 and β with height have been shown to have a significant effect on computed ground-level concentrations. Nevertheless, a possibility exists that there is a layer or a set of heights in the lower atmosphere for which computed z_0 and β values provide computed concentrations in fair agreement with those found experimentally. But here again it is necessary that z_0 and β be uniquely determined for that layer.

In the techniques employed here, values of z_0 for each observation period and values of β for each hour of an observation period were computed from a temperature difference in the vertical and wind speeds from at least two heights. It seems possible that z_0 can be estimated satisfactorily from a description of the height, leafiness, and density of the vegetation, and, in the case of vegetation planted in rows, from a knowledge of the orientation of the wind with respect to the rows. If, at the same time, it can be shown that β, determined from a given set of heights, is a unique function of the Richardson number or the modified form Ri', each β can be found from a temperature difference in the vertical and a single observation of wind speed. Since the determination of β from the stability ratio would be a valuable simplification, it seemed worth-while to examine the relationship between β and Ri'.

For each of the eight observation periods values of β_H were plotted against values of the stability ratio. The β_H–Ri' curves do not coincide. A summary of the curves appears in Figure 3. The curves are grouped with Observation Periods 1 through 4 falling in one group and Observation Periods 5, 7, and 8 falling in another. Period 6 is

TABLE 5 – *Bivariate frequency distribution of β_2 and β_3*

β_2	β_3 0.72–0.74	0.75–0.77	0.78–0.80	0.81–0.83	0.84–0.86	0.87–0.89	0.90–0.92	0.93–0.95	0.96–0.98	0.99–1.01	1.02–1.04	1.05–1.07
1.05–1.07											1	1
1.02–1.04										38	16	
0.99–1.01									11	64		
0.96–0.98								3	40	8		
0.93–0.95								7	7	1		
0.90–0.92							2	3	2			
0.87–0.89							3	5				
0.84–0.86						1	1					
0.81–0.83					2	1						
0.78–0.80					1							
0.75–0.77				1								
0.72–0.74		1	1									
0.69–0.71												
0.66–0.68												

TABLE 6 – *Ratio of peak concentrations (χ_H/χ_L) 100 meters downwind of a continuous point source and an infinite line source*
($z_{0,H}$ = 0.55 cm; $z_{0,L}$ = 0.77 cm)

Conditions	χ_H/χ_L Point source	Line source
u_{2m} (m/sec) = 2 β_H = 0.75 β_L = 0.86	5	3
u_{2m} (m/sec) = 2.5 β_H = 0.85 β_L = 0.92	3	2
u_{2m} (m/sec) = 5 β_H = 1.10 β_L = 1.05	0.5	0.7

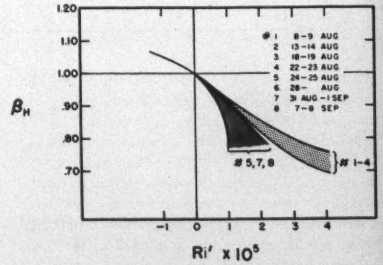

FIG. 3 – Variation of β_H with stability ratio

not included in Figure 3 because its narrow range of stability ratio preclude its placement in one group or another.

Unfortunately, there is a scarcity of points at both ends of each curve. Nevertheless, there is an indication that β_H cannot be uniquely determined from the stability ratio during stable conditions. A similar result is found in the case of β_L. Since there is an increase of z_0, albeit small, from Period 2 through Period 8, it appears that β may be a function not only of the stability ratio but also

of z_0. However, an earlier study [*Barad* and *Davidson*, 1954] of wind profiles measured over a much greater range of z_0 values at Seabrook, New Jersey failed to establish a systematic variation of the β–Ri' curves with the roughness parameter. In the Seabrook data eight values of z_0 fell between 0.005 and 0.05 while seven values fell between 0.15 and 0.70. While the β–Ri' curves varied about an average curve within each set, the two average curves were almost coincident. This result, applied to the O'Neill data and a relatively narrow range of z_0 values, seems to greatly weaken, for the time being at least, the hypothesis that the β–Ri' curves are strongly dependent on values of z_0.

There are good indications that at O'Neill, at least, the period to period variation of β at fixed positive values of the stability ratio is related to the strength of the low level wind maximum at night [*Blackadar*, 1955] (Also unpublished reports by M. L. Barad, Wind data obtained by pibal-swarm method at O'Neill, Nebraska, 9 pp., 1954, and by H. Lettau, Graphs and illustrations of diverse atmospheric states and processes observed during the seventh test period of the Great Plains turbulence field program, 19 pp., 1954). Observations Periods 1, 2, and 3, which have relatively high nighttime values of β, are characterized by weak or poorly-defined jets or wind maxima at night. An example of a weak jet is given in Figure 4, which shows the profile of horizontal wind speed at 02 h 35 m of August 9, 1953. On the other hand, Periods 5, 7 and 8 which have relatively low nighttime values of β are characterized by well-defined jets at night. An example of a well-defined jet is given in Figure 4, which shows the profile of horizontal wind speed at 02 h 35 m of September 8, 1953.

Summary and conclusions—In an analysis patterned after Deacon's, the O'Neill data show a systematic height dependence of β. The variation is such that β decreases with height under stable conditions and increases with height under unstable conditions.

The differences in the observed values of β, together with the differences in the observed values of z_0, introduce significant differences in the theoretical estimates of concentration calculated from diffusion equations containing β and z_0 as parameters.

Moreover, it has been shown that even if the observation levels are fixed from period to period, the β–Ri' curves do not coincide, but seem to be related to the presence or absence of a well-developed nocturnal jet. This relationship suggests that the nocturnal low-level wind profile cannot be specified completely by a knowledge of ground-type and stability near the ground. Complete specification seems to require some knowledge of what is happening to the wind field at some 200 to 400 m above ground. It appears then that an adequate description of low-level flow must include an analysis of parameters on a synoptic as well as a micrometeorological scale.

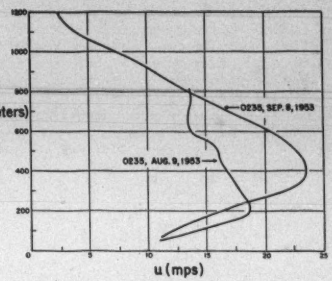

FIG. 4 – Variation of wind speed with height (wind speeds were found from trajectories of ten balloons released at 30-sec intervals)

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Variation of Natural Radioactivity in the Atmosphere with Altitude

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Abstract—The vertical distribution of radon decay products in the lower atmosphere has been measured during airplane flights, using both negative-wire and precipitator methods of sample collection. Data taken by the wire method show a very gradual decrease in activity with height, with considerable activity found to exist at 16,000 ft (msl). The precipitator results indicate an approximately linear decrease with altitude, with no appreciable activity found in samples collected by this method above about 11,000 ft. Measurements made at four ground stations in the altitude interval 4620 to 10,297 ft gave similar results. The mean value for the coefficient of eddy diffusion in the atmosphere calculated from the precipitator data was 7 ± 4 m²/sec for the plane flights and 11 ± 7 m²/sec for the ground stations.

Introduction—Most of the early studies of the vertical distribution of natural radioactivity in the atmosphere showed a marked decrease of activity with height and confirmed the belief that the source of such radioactivity was the uranium and thorium minerals in the Earth's crust. Some recent attempts have been made to use the data for calculating exchange or austausch coefficients for vertical diffusion in the atmosphere [*Israel*, 1951, p. 159; *Garrigue*, 1951; and *Machta*, 1951]. The present work was undertaken in order to measure the vertical distribution of the decay products of radon in the lower atmosphere over central and eastern New Mexico and to use the data obtained in studying vertical diffusion due to turbulence over the area.

Sample collection and measurement—Under generally prevailing conditions near the Earth's surface, the daughter atoms of atmospheric radon have a brief existence as positive atomic ions immediately following disintegration. Recombination may precede or follow subsequent attachment to fine particulate matter normally present in the atmosphere. Because of the high collision frequency of atomic or molecular particles in air, the average life of the radon daughters as positive atomic ions is very short compared with their mean life with respect to radioactive decay. Hence, most of the active atoms present in a given volume of air at a given instant are attached to particulate matter. This mechanism explains why a negatively charged wire exposed to the free atmosphere collects appreciable quantities of radon decay products, and also why an aerosol sample taken from the atmosphere possesses a natural radioactive content. Both methods of sample collection were used in these studies.

The 'negative-wire' collections were made by trailing six meters of no. 26 bare copper wire from the airplane, relative to which the wire was maintained at a negative potential of 2000 volts for a period of ten minutes. At the end of the collection period, the wire was wound onto a flat form for convenience in counting. In the collection of aerosols, samples were deposited on pieces of aluminum foil by means of an electrostatic precipitator. Air from outside the airplane flowed through the precipitator at the rate of 0.22 m³/min. The collections in each case were counted with an alpha scintillation counter and scaling unit. Background and 'standard' counts were taken alternately with each sample count.

Negative-wire collections were made on a total of thirteen flights on nine different days, while precipitator data were obtained on six flights over four days. All equipment for collecting and counting was mounted in a Twin Beechcraft airplane based at Socorro and Roswell, New Mexico.

Flight results—The results of three representative flights for both methods of sample collection are shown in Figure 1. These flights were made over the semi-arid plains near Roswell under normal fair weather conditions. All of the negative-wire data, except those taken on July 10, 1952, 04h51m–07h34m local time, were made in the mid-morning to midafternoon hours in the absence of temperature inversions. Samples taken in regions of cumulus activity or in air masses believed to have originated in regions of recent precipitation were excluded from this study, as were any which showed a marked deviation from the expected decay rate for radon in equilibrium with its daughter products. Statistical errors in counting are shown in the precipitator data. Such errors are negligible in the wire data, and in any event they were smaller than the uncertainty in the value of the collecting field of the wire.

The differences in the data obtained by the two methods are quite marked. The negative-wire collections of July 2, 1952 and July 9, 1952 indicate a

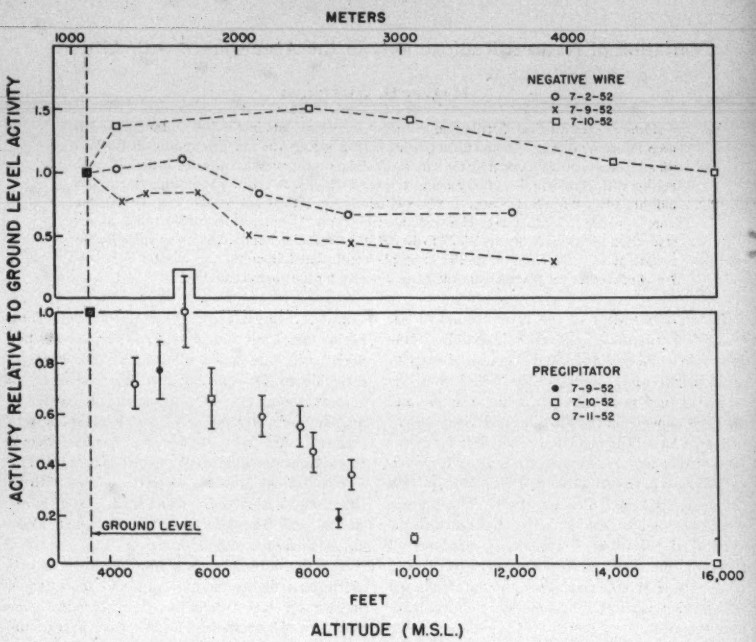

FIG. 1 – Flight data showing relative activity of negative-wire and precipitator collections as a function of altitude

drop in activity at about 6000 ft; otherwise, the decrease with altitude is very gradual. The amount of activity in samples collected by this method (130 counts per minute, 20 minutes after the end of a ten-minute sample collection time for the flight of July 10, 1952) at levels as high as 16,000 ft is noteworthy. The decrease in activity with altitude in the precipitator samples is approximately linear, and on no flight was any appreciable activity recorded above 11,000 ft (about 7000 ft above ground level). This indicates a very low aerosol content, including particles in the submicroscopic size range, at or above this level under typical fair weather conditions. This scarcity of airborne particles at higher altitudes is consistent with observations made on aerosols of microscopic sizes; little is known, however, about the distribution of smaller particles. It is of interest in this connection that the fair weather electrical conductivity of the atmosphere shows a marked increase at about 12,000 ft [*Callahan* and others, 1951]. Since a decrease in the concentration of small airborne particles should produce such an increase in conductivity, this result is in accord with the conclusion drawn from the radioactivity measurements.

The presence of appreciable quantities of radon products in the atomic ion state at altitudes up to 16,000 ft (as indicated by the negative-wire collections) seems reasonable, since the probability of these atoms becoming attached to particulate matter is reduced; hence the wire is able to collect a much greater fraction of the total number of radioactive atoms than is possible at lower levels in the atmosphere. The occurrence of natural radioelements, presumably of surface origin, in a space free of even the smallest aerosols is difficult to explain; the very fine particulate matter (down to 0.003 micron effective diameter) to which the radon products are known to attach [*Wilkening*, 1952a] might be expected to diffuse into the higher atmosphere with nearly the same ease as the atomic radon. Additional data, particularly with respect to decay characteristics of the higher altitude nega-

tive-wire collections, would be of great value in resolving the difficulty.

The contrast between the precipitator and negative-wire data of Figure 1 can be attributed largely, then, to the relative abundance of very fine particulate matter. The negative-wire data cannot be considered to reflect the true radon content as a function of altitude since at the lower altitude the results of a given measurement undoubtedly are affected by the competition afforded by attachment of the ions to minute aerosols. The precipitator measurements, on the other hand, can be considered to give reasonably reliable information in the lower levels or wherever an abundance of fine aerosols exists.

Mountain station measurements—In order to substantiate the limited precipitator data taken during the plane flights and to make further comparisons of the collection methods, a natural radioactivity monitor using the precipitator principle for continuously sampling the atmosphere [*Wilkening*, 1952b] was operated at three mountain stations, in addition to one in the Rio Grande Valley at Socorro. The results are shown in Table 1 where the mean activity at each station has been corrected for the seasonal march in natural radioactivity observed in this locality. The monitor was operated continuously for six days at the Mt. Withington station and for 12 or more days at each of the other stations. The St. Augustine station is located on a high plain surrounded by mountains, and the fact that activity here appears somewhat high, particularly in comparison with that of Water Canyon, can be attributed to absence of mixing due to mountain-valley winds experienced at the Water Canyon station. Similarity between the flight measurements and the ground-station data for the precipitator method is apparent when the relative activity figures for the monitor in Table 1 are compared with the relative activities in the precipitator data of Figure 1. This is evidence that, when time-averaged, the very fine particulate matter concentration in the vicinity of mountains is very similar to that of air over adjacent plains at equal altitudes.

TABLE 1 – *Ground-station activity*

Station	Altitude (MSL)	Monitor		Negative-wire	
		C/min	Relative activity	C/min	Relative activity
	ft				
Socorro	4620	86	1.00	1231	1.00
Water Canyon	6730	65	0.76	920	0.75
Saint Augustine	7000	69	0.80	1056	0.86
Mount Withington	10,297	15	0.17	1533	1.25

As a matter of incidental interest, negative-wire collections also were made at each of the mountain stations. Values shown in Table 1 are calculated from the mean of eight to ten samples at each station. Data were taken during the same time of day at each station, and all within a span of a few days, so that both diurnal and seasonal corrections could be avoided. The unusually high negative-wire activity observed on Mt. Withington, compared with the low activity on the monitor, gives further strong evidence that at higher altitudes an increasingly greater fraction of the total natural radioelements is in the atomic state.

Application to vertical diffusion—If one assumes that the precipitator measurements reflect the true radon content in the lower atmosphere (below 11,000 ft msl or about 7000 ft above ground level in the present case), and that mixing is complete in this interval, the data obtained can be applied to a study of vertical diffusion in the atmosphere. Following the lead of *Schmidt* [1925, pp. 80–83], the number of radon atoms per unit mass of air, N, can be expressed as a function of height z above the ground in an atmosphere of assumed constant density by

$$N = N_0 e^{-(\lambda/K)^{1/2} z}$$

where N_0 is the concentration of radon at ground level, λ is the decay constant of radon, and K is the coefficient of vertical diffusion, due to eddy motion in the atmosphere. This equation is the solution of the differential equation resulting from equating the rate of upward diffusion of radon due to turbulence in the atmosphere to the radioactive decay of the radon. K is assumed height independent. From each point represented in the precipitation data of Figure 1 and from each of the ground stations listed in Table 1, a value of K was calculated. The mean value for the three plane flights is 7 ± 4 m²/sec. The result for the three mountain stations is 11 ± 7 m²/sec. These values fall within the very broad limits found in the literature for the coefficient of eddy diffusion in the free atmosphere. While the data presented are inadequate for a conclusive study of vertical diffusion in the atmosphere, it is evident that experiments of this type could be planned which would be quite useful in investigations of this kind.

Acknowledgment—The author recognizes the assistance of John McCaslin in taking much of the data, and of Theron Young for help in the diffusivity calcula-

tions. The cooperation of the personnel of the St. Augustine and San Mateo Districts of the U. S. Forest Service in making their facilities at the Water Canyon and Mt. Withington stations available is gratefully acknowledged. The work was supported in part by funds from the Office of Naval Research, under contract N7ONR-405/1. Reproduction in whole or in part is permitted for any purpose of the United States Government.

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The Method of Solution of Ruckli's Frost-Penetration Equation

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Abstract—The purpose of this article is to present the author's method of solving a non-linear differential equation given by R. Ruckli expressing the rate of frost penetration in soil. There is no standard method of solution of such a differential equation as set up by Ruckli, yet the method of solution of the non-linear differential equation, not given by Ruckli, is considered to be of great interest to the engineering profession in treating frost-penetration problems in highway and airport engineering.

The author's method of solution of Ruckli's equation for the frost-penetration rate consists of the application and use of power series and the determination of the coefficients involved, thus showing how to arrive at the integral which Ruckli presents as the end result of his non-linear differential equation. The author's thought behind the showing of the method of solution of the equation is not merely to demonstrate the application of so powerful a mathematical tool as the power series for solving engineering problems. According to his belief, it also helps one better to understand the phenomena, nature, and physical processes conveyed by this equation, it enables one better to analyze the problem involved, and establishes in the reader a certain confidence when applying the end result (integral) of Ruckli's equation. In addition, the presentation of this article naturally calls attention to the important work done by Ruckli.

Ruckli's differential equation—As a result of his studies on the significant factor, frost entering into highway design, *Ruckli* [1943] published a mathematical expression for the calculation of the rate of frost-penetration depth into soil

$$d\xi/dt = A/\xi - Bv - C/\sqrt{t} \qquad (1)$$

Assuming that the second term, Bv, is a function of ξ, and to be a linear function, that is, $Bv = f(\xi) = B_1\xi + D_1$, (1) takes the form

$$d\xi/dt = A/\xi - B_1\xi - C/\sqrt{t} - D_1 \qquad (2)$$

The integral (end result) of this non-linear differential equation, representing the frost-penetration depth, ξ, is given by *Ruckli* [1950, p. 159] as

$$\xi = L\sqrt{t}(1 - B_1Rt) - D_1St \qquad (3)$$

where

t = time
v = velocity of the upward flow of soil moisture from ground water toward downward-progressing ice lenses
A, B, B_1, C, D_1, L, R, and S = constants to be determined for any given case.

Assumptions—The assumptions Ruckli made in setting up the differential equation (2) are:

(1) The soil is a homogeneous, semi-infinite body containing free ground water, the table of which is distant H under the ground surface, subjected to atmospheric pressure.

(2) The real temperature profile or curve (= tautochrone) in the soil below the ground surface at a certain time, which is a complex curve, is replaced, for practical purposes, by a simpler curve, a parabola.

(3) The boundary conditions are:

(a) The initial temperature T_0 in the soil is constant; at $t < 0$ and $0 \leq x \leq \infty$, $T_x = T_0 =$ const, where x = depth below ground surface, T_x = temperature at depth x, T_0 = const = initial temperature of soil before freezing.

(b) At time $t = 0$, the cooling process in the soil is inaugurated in that the surface temperature T_s drops suddenly to $T_s < T_0$, and remains so for a certain period of time; under proper thermal gradient, upward suction of soil moisture from ground water toward the growing and downward-advancing ice lenses or crystals takes place; at $t = 0$ and $x = 0$, $T_x = T_s$, where T_s = surface temperature; at $t = 0$ and $x > 0$, $T_{x>0} = T_0$.

(c) At $t > 0$ and $x = 0$, $T_{x=0} = T_s$; at $t > 0$ and $x = \xi$, $T_\xi = T_f = 32°F$, where $T_\xi = T_f =$ freezing temperature; at $t > 0$ and $0 \leq x \leq \infty$, $T_x = f(x; t) < T_0$.

The physical and boundary conditions of this problem are shown in Figure 1.

Unfortunately, Ruckli does not give any hint in his publications as to the method for the solution of (2). Therefore this article presents a condensed method of solution of Ruckli's non-linear differential equation for the calculation of frost penetration depth in soil.

Coefficients A, B, and C—In the following description, indices 1 and 2 refer to the frozen and

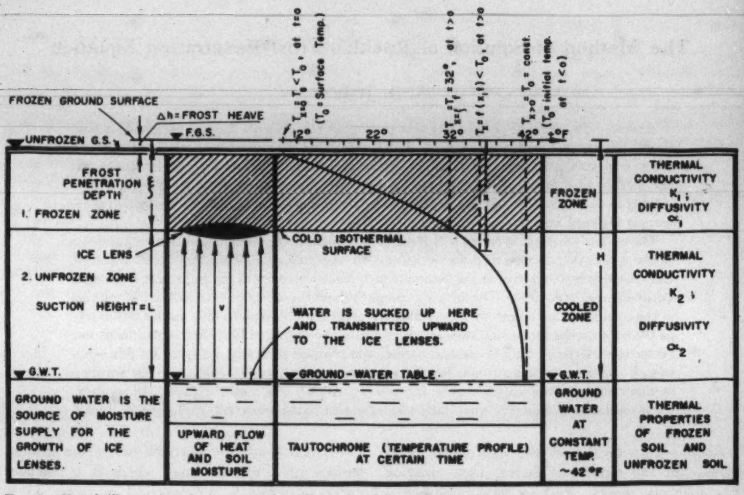

FIG. 1 – Sketch illustrating the concept of unidimensional upward flow of soil moisture toward the frost boundary (or ice lenses) upon freezing; open system

unfrozen zones of soil, respectively. The coefficients A, B, and C in (2) are composed as follows

$$A = \frac{K_1(T_f - T_s)}{(\rho_w n Q_L) + \frac{1}{2}C_1(T_f - T_s) + C_2(T_0 - T_f)} = \frac{K_1(T_f - T_s)}{D} \quad (4)$$

$$B = \rho_w Q_L / D \quad (5)$$

$$C = K_2(T_0 - T_f)\sqrt{(1-m)/3\alpha_2}/D \quad (6)$$

where

K_1 = coefficient of thermal conductivity of the frozen soil layer
K_2 = same for the unfrozen soil layer
α_2 = thermal diffusivity of the unfrozen soil layer
C_1 and C_2 = heat capacities
D = denominator for A as in (4)
T_f = 32°F = freezing temperature
T_s = surface temperature
T_0 = initial temperature
ρ_w = 62.4 lb/ft³ = weight of one cu ft of water
n = volume of voids fully saturated with water
Q_L = latent heat of fusion of ice
m = coefficient, the average value of which is 0.2

Description of differential equation—(a) The first term, A/ξ, in (2) originates from the temperature gradient in the frozen zone of the soil. (b) The second term, $B_1\xi$, comprehends the upward flow, involving the suction head, of the soil moisture from the ground water toward the growing ice lenses (supply of moisture). The negative sign before this term indicates its retarding effect on frost penetration, ξ, into the soil. (c) The third term, $C/\sqrt{t}$, originates from the heat flowing upward from the subsoil to the lower isothermal boundary of the downward advancing frozen layer of soil. This term, too, retards the frost penetration depth. (d) Low surface temperature, T_s, and high coefficient of heat, namely, cold conductivity, K_1, of the frozen zone of soil, facilitate the rate of frost penetration into soil. (e) Water supply by suction from the ground water to the growing ice lenses in soil upon freezing retards frost penetration. (f) A high coefficient of heat, namely, cold conductivity, K_2, of the unfrozen zone of the soil retards the rate of frost penetration into soil. (g) High temperature $T_2 = (T_0 - T_f)$ retards frost penetration. (h) The denominator, D, contains the effect of the thawing heat of the pore or void moisture, and heat capacities, C_1 and C_2. (i) The saturation moisture in the voids of the soil, n, affects the rate of frost penetration retardingly, that is, lower rates of frost penetration in soils of high water content.

The contents and the type of (2) show how difficult it is to try to comprehend mathematically such a complex natural process as that associated with the frost penetration phenomenon in soil, and for which a satisfactory mathematical solution is to be found.

Solution of differential equation—A frequently suggested and satisfactorily practical method for the solution of a non-linear differential equation of the first order such as (2) in solving engineering problems is the application of series. According to theory, every variable can be expanded into a power series, for example

$$\xi = a_0 z^0 + a_1 z + a_2 z^2 + a_3 z^3 + \cdots \quad (7)$$

Such a series is usefully applicable in engineering if it converges.

The boundary condition, based on the physical process, is that when time $t = 0$, there is no frost penetration, and therefore ξ must be zero. Hence the coefficient a_0 must be zero. Multiplication of each term of (2) by the variable ξ and rearrangement give

$$\xi d\xi/dt = A - (C/\sqrt{t} + D_1)\xi - B_1\xi^2 \quad (8)$$

The setting of

$$\sqrt{t} = z \quad (9)$$

yields

$$dt = 2z\,dz \quad (10)$$

which, when substituted in (8), transforms the latter into

$$d\xi^2/dz = 4Az - 4(C + D_1 z)\xi - 4B_1 z\xi^2 \quad (11)$$

The next step is to form by means of the equation of series (7) the quantities $(z\xi)$, ξ^2, $(z\xi^2)$ and $d\xi/dz$. Then substitute these quantities into equation (11), which, after rearrangement and integration, gives

$$\xi^2 = 2(A - a_1 C)z^2 - \tfrac{4}{3}(a_2 C + a_1 D_1)z^3 - (a_2 C + a_2 D_1 + a_1^2 B_1)z^4 - \cdots \quad (12)$$

Comparison of coefficients at the unknown quantities of z^2, z^3, and z^4 in (12) and in the one for ξ^2 formed from the series (7) permits determining the coefficients a_1, a_2, and a_3.

They are

$$a_1 = -C + \sqrt{2A + C^2} \quad (13)$$

Because of its physical nature, the frost penetration depth, ξ, cannot be negative. Therefore a_1 must be positive.

The second term under the radical, namely C^2, is very small, and can be omitted.

$$a_2 = -[(2a_1 D_1)/(3a_1 + 2C)] \quad (14)$$

$$a_3 = -[(a_1^2 B_1 + a_2 D_1 + a_2^2)/(2a_1 + C)] \quad (15)$$

From (13)

$$C = (2A - a_1^2)/2a_1 \quad (16)$$

Elimination of C in (16) from (14) and (15) yields the expressions for a_1, a_2, and a_3. When these latter values are then substituted into (7), it is found that they give the approximative solution for the frost penetration depth, ξ

$$\xi = a_1 z - [(a_1^2)/(a_1^2 + A)]D_1 z^2 - [a_1 B_1/(\tfrac{3}{2} + A/a_1^2)]z^3 \quad (17)$$

When

$$z = \sqrt{t} \quad (9)$$

$$a_1 = L,\ a_1^2/(a_1^2 + A) = S,$$

and

$$a_1/(\tfrac{3}{2} + A/a_1^2) = a_1 R,$$

then

$$\xi = Lt(1 - B_1 Rt) - D_1 St \quad (18)$$

which is the frost penetration depth integral of the non-linear differential (2). It is the same as that given by Ruckli in (3).

Conclusions—(a) The derivation of (2) by Ruckli can be considered as a systematic approach to the solution of the frost penetration problem in highway engineering.

(b) There has been a long-felt need for a simple mathematical expression that would take into account geotechnical and thermal properties of the soil and the migration of soil moisture from ground water toward the growing ice lenses upon freezing (suction force).

(c) However, (2) has the merit of precision just insofar as the physical quantities on which the solution is based can be said to be exact. This is because each of the many individual geotechnical factors in the field varies greatly even within a short distance.

(d) Therefore it can be said that the frost penetration equations (2) and (3) are valid not so much for a special case, but rather for a special range, considering the limiting values of soil geotechnical properties and climatic (thermal) and hydrological conditions.

(e) Although good agreement between calculated and observed frost penetration depths has

been reported, such reports are too few to permit adopting the theory for all geographic, climatic, and soil conditions. Therefore, additional observation and test data are needed to determine the validity and universality of the frost penetration equation.

(f) Because the frost-penetration problem is of great interest to the engineering profession, it deserves further study.

(g) It is hoped that in outlining the method of solution of (2) a service has been done for the engineering profession in that a better insight into this subject matter has been gained and in that the solution is made available for the furtherance and future development of this important but difficult frost-penetration problem.

Acknowledgment—The writer expresses his appreciation to J. J. Slade, Jr., Director, Bureau of Engineering Research, Rutgers University, for the suggestion of solving the non-linear differential equation under consideration.

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An Analytical Derivation of the Darcy Equation

WARREN A. HALL

Abstract—The Darcy equation is derived in general form for non-isotropic porous media from Newton's basic laws of motion and viscosity. The necessary and sufficient additional postulates are: (1) inertia forces of the system are negligible, (2) the liquid films are continuous, and (3) that a volume element of the fluid-porous medium system can be selected which is small compared to the gross dimension of the system yet large enough that the surface area of the matrix therein can be considered to be uniformly distributed throughout the volume element. The equation is shown to be valid for all saturated and non-saturated porous media systems which satisfy these postulates.

The Darcy equation governing the flow of fluids through porous media at small Reynolds numbers has become an accepted basis for analysis of such systems. The equation was first determined experimentally by H. Darcy in 1856 while studying the flow in sand filters. Since that time, ample additional experimental evidence has been obtained as to leave little doubt of its validity for problems in saturated flow of an incompressible fluid. There does not appear to have been an analytical derivation of the equation except possibly for extremely idealized models [*Emersleben*, 1925]. The most satisfying justification to date is probably the dimensional analysis approach such as presented by *Muskat* and *Botset* [1931].

Neither the experimental validation nor the dimensional analysis derivation provides a set of postulates upon which the range of validity might be predicated, nor do they provide proper insight to the application of the Darcy equation to systems wherein the fluid does not fully occupy the pores and for which the capillary conductivity of the soil may vary at each point with the degree of saturation. In the following discussion, the properties of the fluids, the general geometry of the system, and the principles of mechanics are combined with a set of postulates to give a derivation of the Darcy equation. Validity for non-saturated as well as saturated systems is indicated where liquid films are continuous throughout the medium.

Newton's laws of motion may be applied to an element of the fluid flowing through a porous medium. The forces acting on the element are of two general classes, body forces and surface forces. The body forces are proportional to either the mass or volume of the element and may be considered to act at the center of gravity of the element. The surface forces are proportional to the surface area of the element and act on the boundary surfaces of the fluid element. The gravity force is a common example of a body force while pressure and shear forces are examples of surface forces.

Although the pressure force is a surface force, it is equivalent to a body force derived from the pressure gradient. Consider a small element of a fluid of dimensions dx, dy, dz at a point in the fluid as indicated in Figure 1. Summing the indicated forces due to the pressure p in each of the three principal directions

$$\left.\begin{aligned} f_x &= p\,dy\,dz - (p + \partial p/\partial x\,dx)\,dy\,dz \\ f_y &= p\,dx\,dz - (p + \partial p/\partial y\,dy)\,dx\,dz \\ f_z &= p\,dy\,dx - (p + \partial p/\partial z\,dz)\,dy\,dx \end{aligned}\right\} \quad (1)$$

By dividing by the volume of the element, the resultant force per unit volume (body force) due to the pressure variation $\mathbf{f}_p$ is, in vector notation

$$\mathbf{f}_p = -(\partial p/\partial x\mathbf{i} + \partial p/\partial y\mathbf{j} + \partial p/\partial z\mathbf{k}) \quad (2)$$

Introducing the 'del' operator for convenience, the force per unit volume due to pressure variation is

$$\mathbf{f}_p = -\nabla p \quad (3)$$

Eq. (2) is equally valid for the body force per unit total volume acting on the fluid in a porous medium. Consider that the area $dx\,dy$ cuts through a number of soil particles such as the one indicated in Figure 2. Designate that portion of the area $dx\,dy$ which is fluid by $\mathbf{A}_f$ and that which is solid by $\mathbf{A}_s$. The force on the fluid caused by the pressure on the curved surface of the soil particle is equal to $p\mathbf{A}_s$ since the pressure is constant over this area and the vector integral of the curved area is equal to $\mathbf{A}_s$. The total force on the fluid at this face of the element is the sum of the forces on the fluid to fluid boundary $p\mathbf{A}_f$ plus the forces on the fluid to solid boundary $p\mathbf{A}_s$. This total is equal to $p\,dy\,dx$ as in the derivation of (2) which therefore is valid for the force per unit total volume of fluid and porous medium.

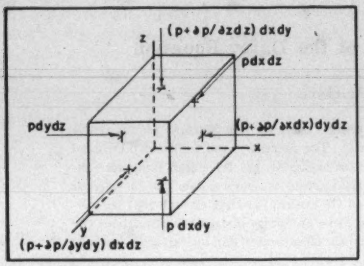

FIG. 1 – Pressure forces on a volume element of fluid

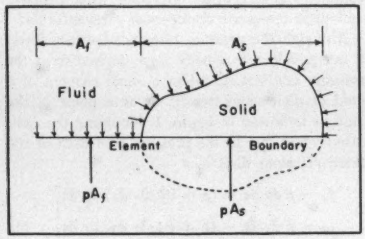

FIG. 2 – Force on an element boundary consisting of both solid and fluid

The gravity force downwards per unit mass f_g' is equal to $\mathbf{g}$, the acceleration of gravity. A potential for this force is given by gz, whose negative gradient is

$$f_g' = -\nabla gz \tag{4}$$

To convert the force per unit mass f_g' to a force per unit volume f_g multiply (4) by the density of the fluid ρ.

$$\mathbf{f}_g = -\rho\nabla gz \tag{5}$$

The force due to gravity on the fluid in an element of the fluid-porous medium system is also the same as that which would occur if the soil particles were replaced by fluid. This may be demonstrated experimentally by weighing a volume of fluid which contains a metal ball suspended by means of a wire as shown in Figure 3. The force F acting on the bottom of the container is the resultant force on the fluid due to the existence of gravity. Summing the indicated forces due to the weight of fluid W_f, the actual weight of the solid W_s and the tension in the wire T, the resultant force on the fluid is

$$F = W_s + W_f - T \tag{6}$$

But the wire tension is equal to the buoyant weight of the ball by Archimedes' principle. If ρ_s and ρ_f represent the densities of the ball and fluid respectively and Q_s and Q_f represent the corresponding volumes of these materials then

$$F = \rho_s g Q_s + \rho_f g Q_f - g(\rho_s - \rho_f)Q_s \tag{7}$$

$$F = g\rho_f(Q_s + Q_f) \tag{8}$$

The resultant force on the fluid per unit total volume is thus simply the specific weight $\rho_f g$ of the fluid whether the solid is present or not. In a porous medium the wire suspension is replaced by the grain to grain contact of the soil particles. By the same reasoning this principle can be extended to cases in which the soil contains a gas phase in addition to liquid.

Eq. (2) and (5) can also be shown to be valid for a non-saturated system if it is postulated that the liquid film is continuous. Figure 4a indicates a sectional view of solid, liquid and gas in a porous medium. The pressure p_l, in this case negative with respect to the gas pressure p_g, is the result of an equilibrium with the force due to surface

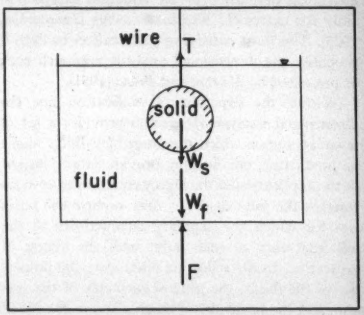

FIG. 3 – Gravity force on a volume of fluid containing a supported submerged solid

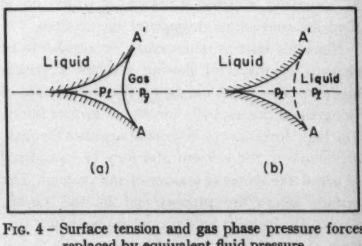

FIG. 4 – Surface tension and gas phase pressure forces replaced by equivalent fluid pressure

tension on the liquid gas interface AA'. If the gas is replaced hypothetically by liquid at a pressure equal to p_l as in Figure 4b, the force due to surface tension on AA' is replaced by liquid pressure without any change on the state of stress on the fluid within the region previously bounded by the meniscus. The force system of the liquid pressure and surface tension of Figure 4a may thus be replaced by the equivalent liquid pressure system of Figure 4b without changing the total force per unit volume due to these causes.

Note that the mass of the fluid whose motion is determined by the above forces is the actual mass of fluid present and does not include the equivalent replacement fluid. Thus although the force per unit volume acting on the fluid is unchanged by the presence of the porous medium or non-saturation, the 'inertia force' or mass times acceleration depends upon the actual mass of fluid which is accelerated. The inertia force is subsequently postulated to be negligible, hence this discrepancy will not enter further into the discussion.

The viscous surface forces cannot be derived from a potential for fluid systems in general. If the surface shearing forces over the interior of a fluid be summed, their resultant is equal to the vector sum of the surface shearing forces on the exterior boundary of the fluid. This equality exists because every elemental area forming a part of the boundary of an interior element of the fluid must also be a part of boundary of an adjacent element or fluid. By the principle of action and reaction, equal and opposite forces must occur on opposite sides of every such interior area. On summing over the entire fluid these force pairs cancel everywhere except on the exterior boundary of the fluid. By this means the surface shearing force on the fluid within the pores is transferred to the matrix of the medium. Therefore, if at any given point the surface area of the solid per unit total volume is independent of the size or shape of the element chosen, the shear force on the fluid within the element can be expressed as an equivalent body force per unit total volume $\mathbf{f}_v$.

Newton's viscosity law provides that, at any point in the fluid, the shear stress τ is proportional to the velocity gradient dv/dh where h is distance normal to the area on which the shear stress acts. The factor of proportionality is the viscosity μ.

$$\tau = -\mu \, dv/dh \tag{9}$$

Let a reference velocity $\mathbf{V}$ at a point be defined as the quantity of fluid per unit time flowing through a unit area of the fluid-porous medium system normal to the net direction of fluid motion. The reference velocity is thus identical to the usual definition of velocity at a point for the Darcy equation. At any point in the fluid within a small volume element of the fluid-porous medium there is a local velocity $\mathbf{v}$. Let the ratio of the x component of the local velocity to the x component of the reference velocity be a_{11}. The corresponding ratio of the y components will be a_{22} and the ratio for the z components will be a_{33}. When a_{11}, a_{22}, and a_{33} are equal, v is parallel to V, otherwise an angle exists between them. The linear vector relationship between $\mathbf{v}$ and $\mathbf{V}$ may thus be expressed as

$$\mathbf{v} = a_{11} V_x \mathbf{i} + a_{22} V_y \mathbf{j} + a_{33} V_z \mathbf{k} \tag{10}$$

The relationship between $\mathbf{v}$ and $\mathbf{V}$ may be expressed more concisely by introducing a second order tensor ϕ

$$\mathbf{v} = \mathbf{V} \cdot \phi \tag{11}$$

The mathematical properties of this tensor are given in standard texts on vector analysis [*Phillips*, 1933, p. 215]. It may be noted that ϕ is a function of time and of the location of the point within the element of volume at which $\mathbf{v}$ is taken. Consider two such points within the element a small distance Δh apart, Δh being normal to the direction of motion. Then by definition of the derivative

$$d\mathbf{v}/dh = \text{limit}\, \Delta h \to 0 (\mathbf{V} \cdot \phi_2 - \mathbf{V} \cdot \phi_1)/\Delta h \tag{12}$$

However the reference velocity does not change as Δh approaches zero so that:

$$d\mathbf{v}/dh = V \cdot \phi' \tag{13}$$

The derivative ϕ' of the tensor ϕ with respect to the scalar h is also a second order tensor. It is also a function of time and position in the fluid within the element of volume under consideration. Let the surface area of the matrix of the porous medium within the element of volume be divided into small area elements ΔA_i. The subscript i is used to identify each element. The element of shear force acting on each element of area ΔA_i is obtained by combining (9) and (13). The direction of the force is parallel to and opposite to the direction of motion just above the surface, that is, $\mathbf{v}$ or $\mathbf{V} \cdot \phi_i'$. The magnitude of the shear force is the product of the area and shear-stress. Thus

$$\Delta \mathbf{f}_i = -\left| \Delta A_i \right| \mu \, \mathbf{V} \cdot \phi_i \tag{14}$$

By summing the elements of viscous shear force over a unit element of volume surrounding the point for which V is defined, the net viscous force

per unit volume of the fluid-porous medium system becomes

$$f_v = \mu \mathbf{V} \cdot \sum_1^n \phi_i |\Delta A_i| \tag{15}$$

The product of a tensor and a scalar is a tensor of the same rank. Likewise the sum of a number of tensors of the same rank is a tensor. The terms represented by the summation in (15) may therefore be replaced by a tensor T.

$$f_v = \mu \mathbf{V} \cdot T \tag{16}$$

Eq. (16) states that the viscous force per unit volume is a linear vector function of the reference velocity. Conversely, the reference velocity is a linear vector function of the viscous force per unit volume. Introducing the tensor K, the reference velocity is given by

$$\mathbf{V} = (1/\mu) K \cdot \mathbf{f}_v \tag{17}$$

The dot product indicated here reflects the non-isotropic conditions of the general case. When the medium is isotropic, K is a scalar and the dot may be omitted.

In the foregoing paragraphs relationships have been found for each of the forces acting on the fluid in a porous medium. A review of the conditions affecting the determination of these forces gives the postulates for the Darcy law. Let it be postulated that: (1) The inertia forces of the flow through a porous medium are negligible. (2) An element of volume of the fluid-porous medium system can be selected at any point which is small with respect to the gross dimensions of the system yet large enough that the surface area of the matrix therein can be considered to be uniformly distributed throughout the volume of the element. (3) Liquid films are continuous. Application of Newton's law under these conditions gives

$$-\nabla p - \rho \nabla g z + \mathbf{f}_v = 0 \tag{18}$$

Substituting equation (18) in equation (17)

$$\mathbf{V} = -(1/\mu) K \cdot (\nabla p + \rho \nabla g z) \tag{19}$$

The tensor K is the permeability. For isotropic porous media, because of the symmetry with respect to any rotation or reflection of the axes, K is simply a scalar whose magnitude may vary with time, location and moisture content. The evaluation of this quantity by analytical means is obviously difficult. It may be determined experimentally for most systems of interest.

The derivation presented is applicable to any flow satisfying the three postulates, including non-saturated flow with a liquid continuum. The permeability may be variable with time and position and may reflect the non-isotropy of the system. The limitations imposed on all fluid systems analyzed by the methods of fluid mechanics are of course implicit. Care should be taken in the application of the law to moisture contents for which the fluid may be but a few molecules in thickness or for which fluid films may not be continuous.

A more convenient form of (19) may be written if the density of the fluid can be considered to be constant. By combining the constant factor $\rho g/\mu$ with the permeability the velocity is seen to be proportional to the gradient of the potential energy per unit weight of fluid expressed as the height of a column of fluid.

$$\mathbf{V} = -k \cdot \nabla (p/\rho g + z) \tag{20}$$

It may be noted from the derivation that adding a term in (20) for the kinetic energy does not give a correction for the neglected inertia forces.

Acknowledgment—The author is greatly indebted to Paul R. Day for technical criticism of the manuscript.

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A Test of the Single- and Double-Ring Types of Infiltrometers

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Abstract—The results of field experiments with ring-type infiltrometers are reported. Infiltration rates obtained with the rings were compared to the infiltration rates obtained by flooding the entire area to determine the number of ring measurements required to characterize the infiltration rate of the area. It was found on a uniform soil profile having no layers restricting the downward movement of water that six infiltrometers gave an average figure that was within 30 pct of the true mean. The single-ring infiltrometers were compared with the double-ring infiltrometers. There was no significant difference in the results obtained with the two types of infiltrometers on a uniform soil under the conditions of the tests.

Introduction—There are several different ways of measuring the relative infiltration rates of soils. Of these, the most convenient to use is the so-called ring-type infiltrometer. In its simplest form the ring-type infiltrometer consists of an open-ended cylinder or pipe placed on the surface of the ground. Water is ponded in the interior of the pipe and the rate of entry of water into the soil is noted. This rate of entry is called the 'infiltration rate' in this paper. Some investigators use a double-ring type of infiltrometer. The double-ring infiltrometer consists of two concentric cylinders. Water is added to the same height in each cylinder. The rate of entry may be measured in both cylinders. The amount of lateral movement is supposed to be indicated by the difference in rates between the inner and the outer cylinder. The outer cylinder is supposed to reduce lateral movement from the inner cylinder and thus give a more accurate value for the infiltration rate.

This paper reports the results of field experiments with the ring-type infiltrometer on an initially wet soil. Two problems were investigated. First, an attempt was made to determine the number of ring measurements required to characterize the infiltration rate of this soil under ponded conditions similar to that occurring during surface irrigation applications. Second, the single and double-ring infiltrometers were compared with each other.

Experimental procedure—Field tests were performed on a series of 40 × 90 foot basins surrounded by a levee approximately two feet high. These basins were constructed in 1938. The basins had lain idle with no cultivation since 1941 with the exception of an annual burning of weeds. At the time of the experiment (1953) the basins were practically free of any plant cover. The soil is a Yolo silt loam with no horizon development.

The basins were first flooded to a depth of approximately 1.5 ft. The time required for the water surface in the basin to subside to a depth of about 0.5 ft was measured. The basin was refilled and the rate of subsidence was again determined. This procedure was repeated four times on each basin. The basins were then allowed to dry for two days after which time the soil surface was dry enough to support a man. Infiltration rates were then measured with ring infiltrometers spaced over the basin on a five-foot grid pattern. Approximately 120 rings were used per basin. Measurements were made on three basins. On two of the basins the double-ring infiltrometers were alternated with the single-ring infiltrometer.

The single rings consisted of six-inch diameter, 20-gauge steel tubes, 16 inches long with the lower edge sharpened. The double-ring infiltrometer was formed by placing a 12-inch diameter metal cylinder concentrically around the six-inch ring.

The rings were pushed into the soil by hand approximately three inches to secure good contact between ring and soil. Care was taken to avoid trampling the soil at the points where the rings were to be placed.

Infiltration rates were obtained by filling the rings to a depth of about ten inches and measuring the time required for the water level to fall to about one inch in depth. The change in water level divided by the time required is reported as the infiltration rate in inches per hour. When the water level above the soil surface fell to one inch, the ring was refilled and the measurement was repeated. A minimum of three fillings was made on each ring. In the case of the double rings, both the outer and inner rings were filled. The rate was measured in the inner rings only. The water level in the outer ring was maintained at approximately the same level as the water level in the inner ring. No measurements were made on the rate of subsidence of the water in the outer ring.

In every case the infiltrometers were placed exactly on the five-foot grid spacing so that the

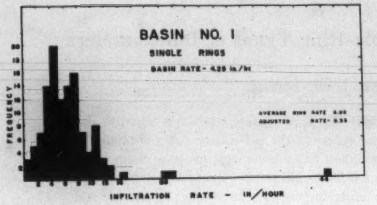

FIG. 1 – Experimental results obtained on Basin 1

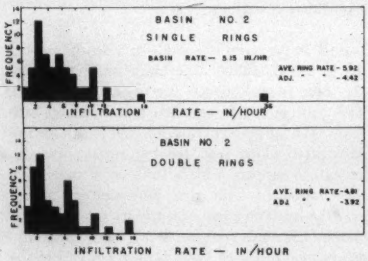

FIG. 2 – Experimental results obtained on Basin 2

sampling distribution would be unbiased. Every reading was recorded regardless of its variation from the remainder of the readings.

Results—All of the infiltration rates reported represent the average rate measured during the second subsidence of the water in the ring or in the basin.

Figure 1 presents the results of 119 determinations made with the single-ring infiltrometer on Basin 1. The results are presented in the form of a frequency-distribution diagram with class intervals of one inch per hour on the abscissa.

The average of the ring-determined rates is 6.60 in/hr. The overall basin rate is 4.25 in/hr which is the average rate of subsidence of water in the basin after the second filling of the basin. Examination of Figure 1 indicates the presence of several values which vary greatly from the average.

If the distribution curve were perfectly normal, the probability of a reading occurring at more than three standard deviations from the mean (SDM) would be 1 in 1000. It was considered desirable to determine a limiting value or range within which readings could be considered as acceptable and beyond which they might be disregarded. This is in an attempt to evaluate the overall basin infiltration rate by using only as many rings as necessary and in addition to have some basis for rejection of erratic values. Such a process must follow the defined rules of statistical analysis. Since the rejection of data would be one-sided here, that is, no low values should be omitted, the criteria for rejection of data on one tail only as outlined by *Rider* [1933] were applied.

An arbitrary value of the true average infiltration rate was assumed by inspection of the data as was the SDM. Values exceeding 3 SDM's were rejected. In the case of the data from Basin 1 an assumed true average infiltration rate of 4.00 in/hr with a SDM of 2.00 in/hr resulted in rejection of all readings over 10.00 in/hr.

The application of these rejection criteria to the data from Basin 1 results in an average of 5.33 in/hr which is within approximately 25 pct of the overall basin rate.

On Basin 2 the single-ring infiltrometers were compared with the double-ring infiltrometers. The frequency distribution diagrams for the results are given in Figure 2. The average of 60

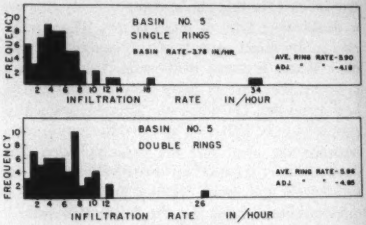

FIG. 3 – Experimental results obtained on Basin 5

TABLE 1 – *Summary of ring and basin infiltration rates*

Basin	Method of determination	Ring spacing	Total no. of rings	Rate	SDM[a]	Adj.[b] rate	Adj.[c] SDM	Adj.[d] no. of rings
		ft		in/hr	in/hr	in/hr	in/hr	
1	Basin	...	...	4.25	...	...	...	...
	Single	5	119	6.60	4.87	5.33	2.19	102
2	Basin	...	...	5.15	...	...	...	...
	Single	10	60	5.92	5.17	4.42	2.38	51
	Double	10	59	4.81	3.63	3.92	2.46	53
5	Basin	...	...	3.78	...	...	...	...
	Single	10	60	5.90	6.20	4.18	2.24	53
	Double	10	59	5.86	4.14	4.85	2.60	52

[a] Standard deviation of the mean using all data.
[b] Adjusted averages after rejecting all data over 10.00 in/hr.
[c] Adjusted standard deviation of the mean after rejecting data over 10.00 in/hr.
[d] Number of rings remaining after rejecting data over 10.00 in/hr.

single rings is 5.92 ± 5.15 in/hr. The average of 59 double rings is 4.81 ± 3.63 in/hr. If all values above 10 in/hr are rejected, the single-ring average becomes 4.42 ± 2.38 in/hr and the double-ring average 3.92 ± 2.46 in/hr. These compare with an overall basin rate of 5.15 in/hr.

Figure 3 shows the data obtained with both single and double-ring infiltrometers on Basin 5. The 60 single rings gave an average of 5.90 ± 6.20 in/hr. The 59 double rings averaged 5.86 ± 4.14 in/hr. Rejection of values over 10 in/hr gives an average of 4.18 ± 2.24 in/hr for the single rings and 4.85 ± 2.60 in/hr for the double rings. In both cases the averages are somewhat higher than the overall basin rate of 3.78 in/hr. The results of the tests are summarized in Table 1.

Discussion—It should be recognized that the data presented here were obtained on a soil having a uniform profile. All of the measurements were made on a wet soil. That is, the moisture content of the soil was at or above the field capacity. The application of these results to other situations must therefore be made with caution. The results would probably differ on soils having well-developed profiles and on soils that are drier than field capacity. These rather severe limitations should be kept in mind in considering the following discussion.

The primary objective of this research was to determine the number of ring infiltrometers required to characterize the infiltration rate of an area of uniform soil. A corollary of this would be the question of the degree of variability one might expect to encounter in a so-called uniform soil. The results indicate that six single-ring infiltrometers randomly spaced will give an average value that is within 30 pct of the true mean. This conclusion was obtained by applying the idea of fiducial limits to the data [*Snedecor*, 1946, p. 456] and was verified a number of times by selecting six random samples from the data. In any sample, data deviating more than three SDM's was discarded. The use of six infiltrometers to characterize the infiltration rate of an area has been previously suggested by *Marshall* and *Stirk* [1950] and *Stirk* [1951]. The degree of variability should be higher on a dry soil that has surface cracks. On the other hand, the soil tested was at or near a natural, undisturbed condition. The Yolo soil tends to be more variable in an undisturbed condition because of the presence of gopher holes, etc. It is believed on the basis of yield observations that any surface treatment of the soil such as discing would tend to reduce the variability of the results.

The use of an arbitrary rejection technique as was applied to these data resulted in average values from ring-infiltrometer measurements which more nearly corresponded to the rates as measured on the same areas by the basin flooding method.

The adjusted ring rates are within approximately 25 pct of the basin rates which might be considered quite close in such a variable system as the soil.

A comparison of the single-ring and double-ring infiltrometers indicates that both types give the same value on the soil tested. This conclusion differs from the results obtained by *Bower* and others [1951] and *Schiff* [1953] who found that the outer ring of the double-ring infiltrometer reduces lateral movement from the inner ring and thus gives a more accurate value for the infiltration rate. The authors attribute this conclusion to the fact that these investigators were working on layered soils having either more compact subsoils or strata which caused an increase in the lateral flow over the vertical flow. In the trials conducted on a uniform Yolo soil having no profile differentiation, there were no impeding layers to cause the water to spread out laterally.

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Discussion

Walter T. Wilson (U. S. Weather Bureau, Washington, D. C.)—This discussion deals solely with the issue of accepting or rejecting reports of extreme values—outliers, as some statisticians

call them. For the concept of a distribution to have any meaning, it must not only have a central value, but also dispersion. Extreme values help determine the mean value, and also the standard deviation or any other measure of dispersion. These extremes are no less part of the distribution than are any of the other values. The mere fact that they depart greatly from the mean is no reason for their exclusion. Extreme departure from the mean may call attention to some individual value, and lead to an investigation of the physical reasons for its extreme value. If this investigation leads to a legitimate reason for rejecting the extreme value—not because it is extreme, but because it 'belongs to a different population,' then it may be excluded.

In an infiltration experiment an extreme value from an infiltrometer might conceivably result from flow through a gopher hole or a root channel. A physical examination might disclose this to be a fact. The question to be answered is whether the experimenter wants to regard gopher holes as natural features of his infiltration area. One of the considerations about gopher holes as legitimate parts of an infiltration area might be whether they lead out of the designated area or not. A proper and more general question is: How do they affect infiltration under test conditions and under operating conditions?

In February 1895, a snowfall of 15 inches in one storm occurred at Galveston, an island in the Gulf of Mexico. This is an accepted fact because it was attested to by official trained observers who state that they measured it, and it is confirmed by other evidence: the sequence of weather at Galveston and the corresponding occurrence of phenomenal snowfall nearby at the same time. Further confirmation may be determined by evidence of natural consequences of an event: there are not only the weather records, but newspapers carried stories and pictures of children playing in the snow. Also, rare as snow may be at Galveston, there is no physical principle that makes it impossible for a foot or so to fall there in one day. However, if the distribution of daily snow falls at Galveston is examined, merely as a distribution, this extreme value might be discarded, with the suspicion that the report arose from a misprint, or other error of some sort. But if an investigator is interested in physical processes, he examines other relevant evidence, in an effort to understand what happened. This process of inquiry seems to be superior to the occasional practice of assuming that a line separating the dichotomy of valid vs unvalid reports can be found merely by choosing an arbitrary point along a frequency distribution.

Durov's Classification of Natural Waters and Chemical Composition of Atmospheric Precipitation in USSR: A Review

GEORGE V. CHILINGAR

Abstract—The present review contains Durov's method of classifying natural waters on the basis of ionic composition. The chemical composition of atmospheric precipitation in USSR is also presented.

Durov's classification of natural waters—Durov [1948], who is one of the foremost Soviet hydrologists, divided the natural waters into five classes.

Class I (primary waters)—The simplest or primary waters result from the action of atmospheric precipitation on the Earth's surface which was leached of the readily soluble salts. These waters containing CO_2 easily dissolve limestones and dolomites and, therefore, reach a state of chemical equilibrium with respect to the solution of calcium and magnesium bicarbonates under the prevailing conditions.

The primary waters are only slightly mineralized (100–300 mg/l and less), with Ca/Mg ratio varying from 5 to 10 (apparently in equivalents). The sulfates and chlorides are either absent or present in very small amounts (<0.2 mg-equ/l or ten per cent mg-equ).

Class II (secondary waters)—The secondary waters result from the enrichment of primary waters with sulfates and chlorides of sodium and magnesium which are present in sedimentary rocks. The mineralization increases to 500–1000 mg/l and, occasionally, exceeds 1000 mg/l. Hardness also increases, whereas the Ca/Mg ratio decreases from 3.3 to 1.4 (and less).

The secondary waters acquire $CaSO_4$ as a result of direct solution of gypsum or the following reaction

$$Ca(HCO_3)_2 + MgSO_4 \rightarrow CaSO_4 + Mg(HCO_3)_2$$

Class III (sulfate waters)—The sulfate waters result from secondary waters upon removal of bicarbonates and if the chlorides are of secondary importance. The concentration of secondary waters in closed basins results in the conversion of bicarbonates to slightly soluble carbonates, which precipitate out. Further concentration of these waters eventually gives rise to the sulfate lakes.

The removal of bicarbonates from the secondary waters can also occur as a result of oxidation of pyrite

$$FeS_2 \rightarrow FeSO_4 \rightarrow Fe_2(SO_4)_3 \rightarrow Fe(OH)_3 + H_2SO_4$$

According to *Durov* [1948], the products of this reaction, namely sulfuric acid and ferric sulfate, convert the magnesium and calcium bicarbonates into sulfates. The significance of $Fe_2(SO_4)_3$ in converting the bicarbonates into sulfates, however, is questionable because of its slight solubility in water.

The transitional waters between Classes II and III contain both bicarbonates and sulfates of magnesium. These waters are very corrosive in steam boilers.

Class IV (chloride waters)—As a result of enrichment with chlorides and simultaneous loss of bicarbonates and sulfates, due to precipitation of $CaCO_3$, $CaMg(CO_3)_2$, and $CaSO_4$, the secondary waters change to chloride-predominant waters. These waters appear to be the most stable and result from gradual evaporation in the closed basins. Their formation is also accompanied by cation exchange giving rise to the calcium and magnesium chlorides.

Class V (alkaline bicarbonate waters)—The alkaline waters could have formed from the secondary waters upon colloidal-chemical removal of the $Ca^{\cdot\cdot}$, $Mg^{\cdot\cdot}$, and SO_4'' ions by fresh-water clays, etc.

$$Ca(HCO_3)_2 + Na_2SO_4 \rightarrow CaSO_4 + 2NaHCO_3$$
$$Mg(HCO_3)_2 + Na_2SO_4 \rightarrow MgSO_4 + 2NaHCO_3$$

The alkaline waters are commonly devoid of sulfates, with no notable evidence of biochemical processes. The biochemical processes, however, probably also contributed to the formation of these waters. Low mineralization, low hardness, and low Ca/Mg ratios are also characteristic of alkaline waters. Upon concentration, these alkaline bicarbonate waters give rise to soda lakes.

Durov's diagram (Fig. 1) is a double triangular diagram, where in one triangle the composition of water is expressed in terms of HCO_3', SO_4'', and Cl' anions, whereas the points plotted in the other triangle show the relative proportions of $Ca^{\cdot\cdot}$, $Mg^{\cdot\cdot}$, and $Na^{\cdot}$ cations. The amounts of these

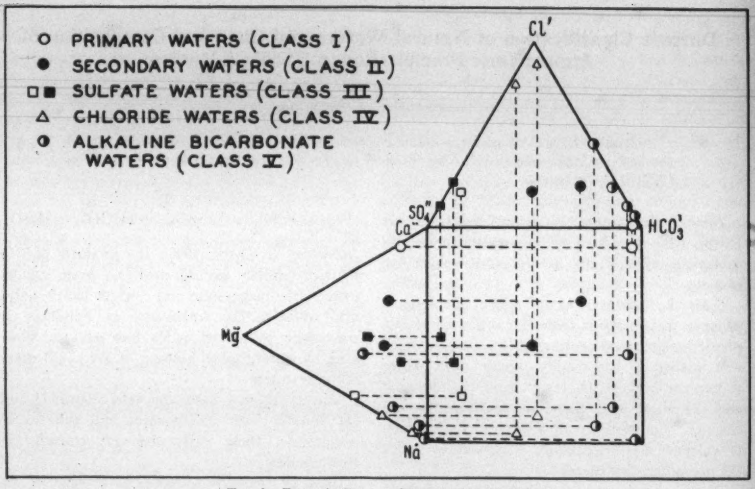

FIG. 1 – Durov's diagram [*Durov*, 1948, p. 90]

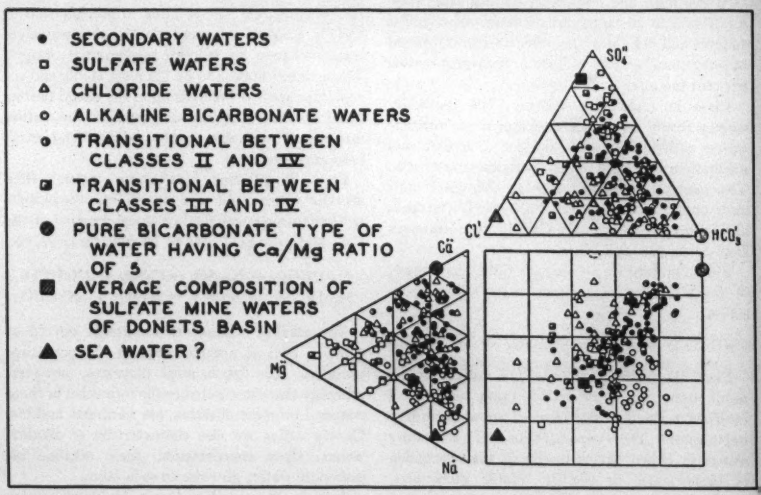

FIG. 2 – Ionic composition of atmospheric precipitation in USSR plotted on Durov's diagram [*Durov* and *Fedorova*, 1955, p. 664]

ions are expressed in per cent mg-equivalents, taking the sum of anions and cations as 100 pct each. In plotting these points, the CO_3'' anion is combined with HCO_3', and $K^{\cdot}$ cation with $Na^{\cdot}$.

In order to obtain a point inside the square, perpendiculars are drawn from the two points plotted in the triangles, and extended until they intersect. In Durov's square, the points occupying the upper

right corner represent the primary waters, whereas the points representing mine waters (black squares), waters of sulfate lakes (open squares), chloride waters (open triangles), and soda waters (semi-open circles) are located along the periphery in the opposite part of the square. The points located along the HCO_3'—Na^+ diagonal represent the secondary waters (black circles), and show change from the $Ca(HCO_3)_2$ to Na_2SO_4. The transition from the secondary to alkaline waters occurs along the direction perpendicular to the above mentioned diagonal, as a result of loss of $CaSO_4$ and $MgSO_4$.

Ionic composition of atmospheric precipitation in USSR—Fedorova [in *Durov* and *Fedorova*, 1955] analyzed 190 samples of atmospheric precipitation (rain, snow, and hail, together with salts of various origin brought down by them) from 41 hydrometeorological stations in USSR. About half of these stations were located along the shores of Black Sea, Azov Sea, Arctic Ocean, and Sea of Okhotsk. The results of her analyses were subsequently plotted on Durov's diagram (Fig. 2).

The examination of Figure 2 reveals the absence of primary waters. Eighty three samples belong to Class II (black circles); 19, to Class III (open squares); 36, to Class IV (open triangles); and 36, to Class V (open circles). Five samples are transitional between Classes II and IV (semi-open circles), and 11 samples are intermediate between Classes III and IV (semi-open squares). The examination of Figure 2 also reveals that the major portion of points is located between the following two points: (1) big dashed circle representing a pure bicarbonate type of water, having a Ca/Mg ratio (in equivalents) of 5; and (2) big black square showing the average composition of sulfate mine waters of Donets Basin, over the period of 40 years—1911–1951. The absence of points near the gypsum point (dotted) probably indicates that the direct solution of gypsum made very small contribution to the chemical composition of atmospheric precipitation.

Most of the samples (72.6 pct) belong to the continental type of waters (Classes II, III, and V). These waters are obviously not of marine origin. The composition of chloride waters, however, also differs markedly from the sea water. These results are in close accord with those of *Maksimovich* [1953], who calculated that the salts of continental origin constitute 67 pct of all salts present in the atmospheric precipitation of USSR.

The average ionic composition of 190 samples

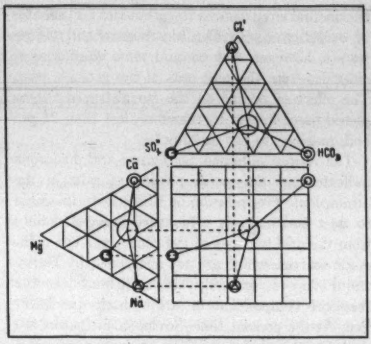

FIG. 3 – Average chemical composition of atmospheric precipitation in USSR [*Durov* and *Fedorova*, 1955, p. 665]

TABLE 1 – *Average chemical composition of atmospheric precipitation in USSR*

Ion	Composition	Aver. pct equ	Pct equ of different salts			Sulfates (pct of total sulfates)
			Marine salts	Bicarbonates	Sulfates	
	mg/l					
Mg^{++}	1.74	26.53	4.77	8.90	12.86	44.8
Ca^{++}	4.82	40.00	0.95	35.48	3.57	12.5
Na^+	5.12	33.47	21.23	...	12.24	42.7
		100.00	26.95	44.38	28.67	100.0
HCO_3'	18.20	44.45	0.07	44.38	...	...
SO_4''	9.17	31.18	2.51	...	28.67	100.0
Cl'	5.46	24.37	24.37	...	...	...
	44.51	100.00	26.95	44.38	28.67	100.0

of atmospheric precipitation analyzed by Fedorova is presented in Figure 3 and Table 1.

Apparently, in calculating the per cent equivalents (pct equ) of various salts, it was assumed that all Cl' (24.37 pct equ) is of marine origin; and the pct equ of other ions in the 'marine salts' column were made to correspond to the percentage composition of dissolved solids in sea water (same proportions). The pct equ of other salts were calculated by the process of elimination—remainder of HCO_3' (44.45 − 0.07 = 44.38 pct equ) belonging to bicarbonates, remainder of SO_4'' (31.18 − 2.51 = 28.67 pct equ) belonging to sulfates, etc.

Conclusions—According to *Durov* and *Fedorova* [1955], the marine salts constitute only about 27 pct of all salts present in the atmospheric precipitation. The remainder of salts can form in the

continental environment (bicarbonates and sulfates of oxidation zone). The bicarbonate and sulfate waters, however, also contain some admixture of chlorides from the relic seas of the geologic past. The effect of oceans on the chemistry of atmospheric precipitation is, therefore, less than 25 pct and, possibly, as low as 20 pct.

The results obtained by Durov and Fedorova indicate that the major portion of salts in the atmospheric precipitation of USSR owes its origin to dust and aerosols, which are brought mainly from the arid portions of the continent. The man-made sources, which are not mentioned by Durov and Fedorova, probably also contributed to the chemical composition of atmospheric precipitation. At the present time, Soviet investigators are studying the places of origin of dust masses and directions of their migration.

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[a] The Russian references listed in the bibliography can be obtained through interlibrary loan from Miss Mildred Oelke, Head of Technical Library, Wright-Patterson Air Force Base, Dayton, Ohio.

Application of the Modified Einstein Procedure for Computation of Total Sediment Load

K. B. Schroeder and C. H. Hembree

Abstract—A method that enables good estimates to be made of total sediment load has been tested with data from several western streams. The method, which uses both theoretical and empirical formulas, combines a modification of Einstein's procedure for computing bed-material load and the usually available data from suspended-sediment measurements. Basic data, including data from large natural and artificial turbulent flumes, and the results of computations are given.

Introduction

The planning for water-resources development in the Niobrara River basin in Nebraska by the U. S. Bureau of Reclamation in 1945 indicated a need for sediment investigations in the area. At the request of the U. S. Bureau of Reclamation, the U. S. Geological Survey began a systematic study of the suspended-sediment discharge at selected stream-measuring stations. Several of the stations had wide and shallow cross sections, whereas others were deep and narrow. Preliminary results from the investigations in these shallow sand-bed streams pointed out the variation in the relationship between the suspended load and the total load at cross sections that have different widths and depths.

Sediment transport at a particular point is a function of the sediment concentration at the point multiplied by the water velocity at that point. The depth-integrating samplers are designed to admit the water-sediment mixture at the stream velocity. Hence, uniform movement of the sampler through the sampling depth integrates the sediment transport, or the concentration times velocity relationship, in the sampled depth. In practice, the sediment load in tons per day is computed by multiplying the concentration in parts per million by the discharge in cubic feet per second by a conversion factor, normally 0.0027.

Figure 1 is a diagrammatic sketch that illustrates the measured and unmeasured concentration. The sketch is of a DH-48 sampler (depth-integrating hand sampler), which will sample sediments within about 0.3 of a foot of the stream bed. The unsampled depth is slightly greater for cable-suspended samplers.

The concentration determined from a depth-integrated sample is assumed to represent the velocity-weighted concentration of suspended sediment from the surface to the stream bed. Because the concentration in the unsampled zone exceeds the velocity-weighted concentration in the sampled depth, the computed suspended-sediment load is less than the actual suspended-sediment load. Therefore, the unmeasured discharge of suspended sediment is represented by the excess concentration of suspended sediment at each point in the unsampled depth multiplied by the velocity at each point. Also, sediment particles transported in more or less continuous contact with the bed are part of the unmeasured sediment discharge and are not included in the computed suspended-sediment discharge.

Figure 2 is a diagrammatic sketch of a velocity-concentration curve versus depth of a 1.5-foot sampling vertical on one of the shallow sand-bed streams in the Nebraska sandhill area. This curve is a combination of the vertical-concentration curve and the vertical-velocity curve. The bottom of the curve is left open because of the impossibility of estimating bed-load discharge from point samples. The sketch is illustrative only, and accuracy at the extremities is not implied. However, Figure 2 does emphasize the fallacy of assuming that the sediment transport can be computed by multiplying measured concentration, which is obtained by integrating only to the sampling limit, by the total water discharge.

The uncertainty as to the amount of unmeasured sediment load in sandhill streams led to the design and installation of a turbulence flume for measuring total load on the Middle Loup River near Dunning, Nebraska. Operation of this flume was begun in June 1949. Also, in April 1948, a sediment-sampling station was installed at a contracted, natural rock section on the Niobrara River near Cody, Nebraska, where essentially total load could be measured. Studies for the total-load and normal sections at these two locations show that for the wide, shallow, sand-bed streams, the unmeasured sediment load can often vary from 20 to 60 pct of the total; the variation depends on the

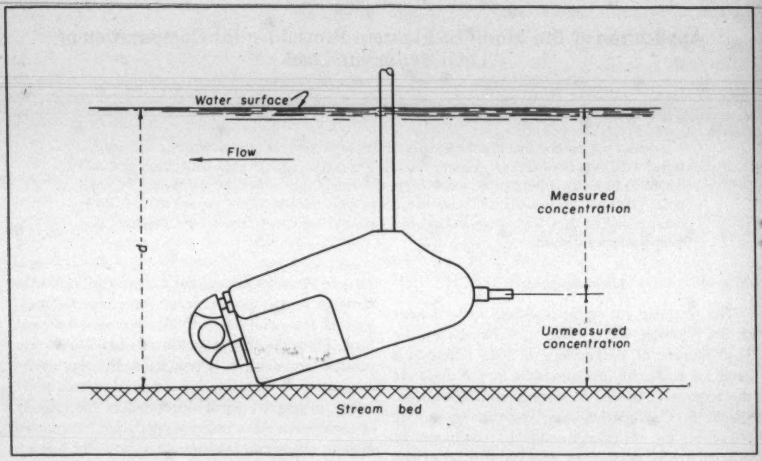

FIG. 1 – Sampling limit of a DH-48 depth-integrating hand sampler

type and hydraulic conditions of the sampling section. The proportion of the total sediment discharge that is unmeasured varies greatly with the particle size and the depth of the stream.

Establishment of the sediment-sampling stations where total load can be measured permitted a study of various methods for the determination of the total load at stream sections where total load cannot be measured. Comparison of the measured total load with the computed total load obtained for typical sections or reaches upstream or downstream indicated the method most applicable for computing total load.

The studies were conducted with the following main objectives: (a) The computed load should be reasonably accurate for all size fractions. (b) The method should be one that utilizes data that can be collected by the average hydrographer and with the equipment presently available. (c) The method should be economical because determinations of total load were to be made at many stations.

One of the points that came up early in the investigations was the relationship between the computed results at the typical alluvial section and the measured results. The available formulas either computed various fractions of the load that overlapped the measured load or left some of the load undefined. Hence the term 'unmeasured load'

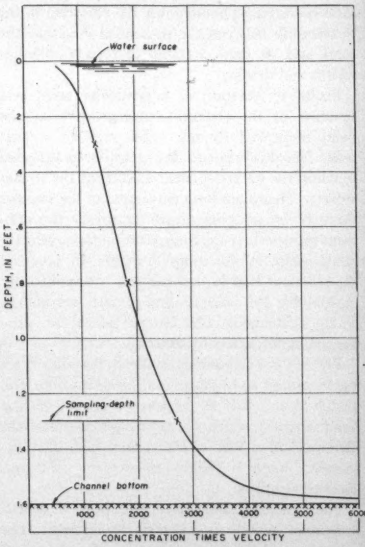

FIG. 2 – Diagrammatic sketch showing vertical distribution of sediment discharge in a shallow, sand-bed stream

became basic, and the combining of the load computed by the then existing formulas with that measured was a definite problem.

Several studies of sediment transport on sandhill streams have been published [*Serr*, 1950; *Colby*, *Matejka*, and *Hubbell*, 1953]. Results of studies on the Middle Loup River near Dunning are being prepared for publication. Studies on the Niobrara River near Cody, Nebraska, led to the development of the modified Einstein procedure [*Colby* and *Hembree*, 1955].

The purpose of this paper is to show the results of the application of the modified Einstein procedure on sandhill streams in Nebraska and on some streams outside the area and to show that the results appear reasonable.

Outline of modified Einstein procedure

The U. S. Department of Agriculture published a paper by *Einstein* [1950] on a method of computing bed load and that part of the suspended load made up of bed material. Einstein related bed load and suspended load with the use of the bed-load transport in the bed layer, which he defined as two grain diameters thick, to determine the concentration at the lowermost depth of suspended load. He employed a new procedure for summing the sediment transport of particles of several size classes to determine the total bed-material load. Also, he developed the procedure for subdividing the area and the hydraulic radius of a stream into components, only one of which is important in determining the effect of shear on the particles at or moving on the stream bed. Some familiarity with Einstein's paper, the symbols used, and his terminology is helpful in understanding the modified Einstein procedure.

In the modified Einstein procedure, many of the basic ideas of Einstein are used. However, the modification was developed from a different set of field data and includes the use of measured data as much as possible.

Basic data required for computation of total load by the modified Einstein procedure consist of readily measurable data at a single section. These data are usually obtained as a part of the routine operation of a suspended-sediment station and are as follows:

(1) Discharge measurement
  (a) Stream width
  (b) Average velocity of flow
  (c) Mean depth
(2) Depth-integrated suspended-sediment samples
  (a) Concentration of suspended sediment in the sampled zone
  (b) Mean depth of the sampling verticals
  (c) Particle-size analyses
(3) Bed-material particle-size analyses
(4) Water temperature

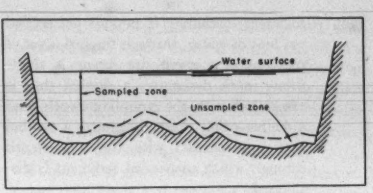

FIG. 3 – Profile of a normal section and outline of sampled and unsampled zones

Briefly, the modified Einstein procedure consists of the integration of sediment discharge for each size class from the water surface to the top of the bed layer; the computation of sediment discharge through the bed layer of particles of a size class; and the summation, for each size class, of sediment discharge through the bed layer and the remainder of the total sediment discharge.

In each range of the small particle sizes, the sediment discharge is computed by multiplying the suspended-sediment discharge in the sampled zone by the ratio of theoretical total suspended-sediment discharge in the size range to the theoretical suspended-sediment discharge of the same particle sizes in the sampled zone (Fig. 3). The ratio is computed by dividing the integrated products of theoretical velocity and theoretical concentration from the stream surface to the top of the bed layer by similar integrated products from the stream surface to the lower limit of the sampled zone. In the size ranges of the larger particles, the total sediment discharge is computed in about the same way as explained by Einstein except that different methods of computation are used for the exponential measure of the increase in sediment discharge with depth, the shear velocity with respect to the sediment particles, and the intensity of bed-load transport.

For a given time at a given cross section of a stream

$$\frac{q_s'}{i_B q_B} = \frac{I_1''}{J_1''}\,(PJ_1' + J_2') \qquad (1)$$

in which

q_s' = discharge of suspended sediment of a given size range per foot of width in the sampling zone, and

$i_B q_B$ = sediment discharge, in pounds per second per foot of width, through the bed layer of particles of a given size range. A single prime mark designates a symbol that is associated with the sampling depth, and a double prime mark designates a symbol that is associated with the total depth through which suspended sediment is discharged.

Other symbols introduced by Einstein as abbreviations of certain functions are

$$J_1 = \int_A^1 \left(\frac{1-y}{y}\right)^z dy$$

$$I_1 = 0.216\,\frac{A^{z-1}}{(1-A)^z}\,J_1$$

$$P = 2.303 \log \frac{30.2\,xd}{k_s}$$

$$J_2 = \int_A^1 \left(\frac{1-y}{y}\right)^z \ln (y)\, dy$$

in which

d = depth of water, except when it is used as a sign of differentiation

A = distance from the stream bed to the lower limit of integration divided by the depth d; A and 1, the limits of integration, are relative distances above the stream bed

y = distance above the stream bed

x = dimensionless parameter for transition from smooth to rough boundaries

k_s = roughness parameter, that particle size for which 65 pct of the bed material by weight is finer

z = theoretical exponent for vertical distribution of sediment

The discharge of suspended sediment in the sampling zone for each size range, Q_s', can be computed from size analyses and concentrations of depth-integrated samples and from water discharge through the sampled zone. The bed-load discharge, $i_B Q_B$, in tons per day, is obtained by modifications of Einstein's procedure.

In the modified procedure the shear velocity, $\sqrt{32.2\ (SR)_m}$, is computed by modifying Eq. (9) of *Einstein* [1950, p. 10], thus

$$\hat{u} = 5.75\,\sqrt{32.2(SR)_m}\,\log \frac{12.27\,xd}{k_s} \qquad (2)$$

or

$$u_m = \frac{\hat{u}}{5.75 \log \dfrac{12.27\,xd}{k_s}}$$

in which

$\hat{u}$ = average velocity for the cross section and may be taken from a streamflow measurement

$(SR)_m$ = quantity that is obtained by solving equation (2) for SR from a known numerical value of $\hat{u}$

u_m = shear velocity equal to $\sqrt{32.2\ (SR)_m}$

The equation for the shear intensity of bed-load transport given by *Einstein* [1950, p. 37, Eq. 49 and 54] is

$$\Psi_* = \xi Y(\beta/\beta_x)^2(S_s - 1)\,\frac{D}{S_s R'} \qquad (3)$$

in which

ξ and Y = two correction factors

β and β_x = certain logarithmic functions

S_s = specific gravity of the sediment particles

D = geometric mean diameter of the sediment particles of a size range

R' = hydraulic radius with respect to the sediment particles

S_s = slope of the energy gradient

Also, *Einstein* [1950, p. 10] states that sediment transport "is a function of a flow function of the type"

$$\Psi = (S_s - 1)\,\frac{D_{35}}{S_s R'} \qquad (4)$$

in which

D_{35} = particle size of the bed material at which 35 pct by weight of the grains is finer

In the modified Einstein procedure $\xi Y(\beta/\beta_x)^2$ is replaced by 0.4 and $S_s R'$ is replaced by $(SR)_m$ in (3) and (4), respectively, and Ψ and Ψ_* are replaced by Ψ_m, which is computed for each geometric mean particle size as the larger of two alternates from

$$\Psi_m = 0.4\,\frac{1.65\,D}{(SR)_m}$$

$$\Psi_m = \frac{1.65\,D_{35}}{(SR)_m}$$

The second equation is thus used when D is less than 2.5 times D_{35}.

The intensity of bed-load transport Φ_*, determined from Einstein's Φ_* to Ψ_* graph by using Ψ_m as if it were Ψ_*, is divided by 2 to make computed sediment discharges agree better with

measured total sediment discharge. The bed-load discharges $i_B Q_B$, in tons per day, for each range of particle size through the entire cross section are computed from

$$i_B Q_B = \left(\frac{\Phi_*}{2}\right) 1{,}200\, D^{3/2} i_b\, 43.2 w$$

$$= 25{,}900\, \Phi_*\, D^{3/2} i_b\, w$$

in which

$1{,}200 = s_s g^{3/2}(S_s - 1)^{1/2}$

43.2 = coefficient for changing sediment discharge in pounds per second to tons per day

w = width of the channel, in feet

i_b = fraction of bed material in each size range

The suspended-sediment load of a given size range for the sampled zone can be computed from (1) as

$$\frac{Q_s'}{i_B Q_B} = \frac{I_1''}{J_1''}(PJ_1' + J_2') \qquad (5)$$

The concentration of suspended sediment of a given size in a vertical section has been expressed as an exponential function whose slope or exponent is z. The exponent is designated as z_1 when determined from data of point-integrated samples. An exponent may also be determined that will satisfy the data from depth-integrated samples provided the concentration is defined at one point of the vertical section. When the point is at the bed layer, the exponent can be computed by a trial-and-error solution of (5) if Q_s' has been determined for an alluvial section. This exponent has been designated as z_2. In the modified Einstein procedure, z_2 is determined for one size class. From analyses of field data [*Colby* and *Hembree*, 1955], z_2 for the other size classes is determined from a proportionality of the 0.7 power of the settling velocities of the geometric mean size of the particles. (The settling velocities [*Rubey*, 1933] are from one of Einstein's graphs and are adjusted for differences in temperature.)

Comparison of computed and measured total loads

Computations of total sediment discharge have been made for cross sections near several natural and artificial turbulence flumes where total load or nearly total load can be measured. Comparisons of the total load computed at a normal section have been made with the load measured at the turbulence flume. The agreement between the two loads is an indication of the accuracy of the computation procedure. However, because the total measured load at the flume is not necessarily the same as the total load at an adjacent section at an equivalent time of measurement, the comparison of numerous pairs of computations and measurements is necessary to provide a quantitative measure of the accuracy of the procedure.

Tables 1 to 5 give comparisons between the computed total loads and the loads measured at contracted sections. Also, a breakdown of the loads by size ranges is given. There is good agreement between the computed and measured loads, not only for the totals but also for each size range. Reasonably accurate data on the size distribution of the total load are essential for the planning of any hydraulic structure or project. The computed total loads shown in this paper, except those for the Mississippi River, are based on data from stations operated as a part of the program of the Department of the Interior for the Missouri and Rio Grande basins. The station on the Mississippi River at St. Louis is operated by the Geological Survey in cooperation with the Corps of Engineers.

Niobrara River near Cody, Nebraska—The Niobrara River near Cody is a typical sandhill stream flowing in a wide, shallow, sand-bed channel without much lateral confinement. The flood plains are in a canyonlike valley, some 200 ft below the uplands (see Fig. 4). The flow of sandhill streams is predominantly derived from ground-water accretions, and the sediments transported are picked up from the stream channel.

Periodic sediment measurements have been made near the gaging station and at other nearby relatively unconfined sections for comparisons with measurements at the contracted section. The contracted section is at a county bridge over a chute that was formed by entrenchment of the stream in argillaceous siltstone (Fig. 5). About 50 ft upstream from the bridge and contracted section, the chute is only two or three ft wide at the water surface; the sediment is not yet entrained at this narrow, swift end. The chute expands to a width of about 11 ft at the bridge, and the flow becomes slower.

Comparisons of the results of computations of total load at three normal sections with total load measured at the contracted section are given in Figure 6 and Table 1. In 24 comparisons, the computed total sediment discharge ranged from 56 to 187 pct and averaged 97 pct of the measured sediment discharges at the contracted section. If two of the computations were omitted because of unrepresentative suspended-sediment size distribu-

tions, the remaining comparisons would range from 66 to 146 pct and average 95 pct of the measured sediment discharges at the contracted section [*Colby* and *Hembree*, 1955].

Middle Loup River at Dunning, Nebraska—The artificial turbulence flume at Dunning was completed in May 1949 and has been described by *Serr* [1951]; *Benedict* and others [1955]. The flume

TABLE 1 – *Comparison of measured sediment discharge and computed total sediment discharge at the normal sections with measured sediment discharge at the contracted section of the Niobrara River near Cody, Nebr.*

Date	Water discharge	Section	Type of sediment discharge	Sediment discharge in tons per day								Percentage of sediment discharge at the contracted section
				Finer than 0.062 mm	0.062 to 0.125 mm	0.125 to 0.25 mm	0.25 to 0.50 mm	0.50 to 1.00 mm	1.00 to 2.00 mm	2.00 to 8.00 mm	Total	
1950	cfs											
Mar. 3	392	Gaging station	Measured	325	358	392	45	...	...	...	1120	60
		Gaging station	Computed	328	436	883	411	57	6	2	2120	113
		Contracted	Measured	243	374	842	337	19	56	...	1870	100
May 11	566	Gaging station	Measured	318	588	604	80	...	...	...	1590	48
		Gaging station	Computed	324	725	1345	675	89	12	6	3180	95
		Contracted	Measured	301	501	1470	969	100	...	...	3340	100
Aug. 30	376	Gaging station	Measured	437	204	281	48	...	...	...	970	55
		Gaging station	Computed	436	251	649	351	46	4	1	1740	99
		Contracted	Measured	475	229	493	493	70	...	...	1760	100
1951												
Apr. 27	440	Gaging station	Measured	187	385	437	31	...	...	...	1040	46
		Gaging station	Computed	190	473	948	504	70	7	3	2200	98
		Contracted	Measured	269	448	829	582	112	...	...	2240	100
May 10	314	Gaging station	Measured	76	175	222	...	...	...	...	473	36
		Gaging station	Computed	77	218	561	316	44	4	1	1220	92
		Contracted	Measured	93	213	559	426	40	...	...	1330	100
1952												
June 19	230	Gaging station	Measured	43	57	145	40	...	...	...	285	59
		Gaging station	Computed	44	67	259	133	11	...	...	514	107
		Contracted	Measured	53	67	216	130	14	...	...	480	100
Sep. 26	234	Gaging station	Measured	31	50	114	24	...	...	...	219	47
		Gaging station	Computed	31	63	226	108	10	...	...	438	94
		Contracted	Measured	42	65	223	126	9	...	...	465	100
1953												
July 8	278	Gaging station	Measured	81	117	135	21	...	...	...	354	60
		Gaging station	Computed	82	142	291	149	15	1	...	680	114
		Contracted	Measured	89	125	202	142	18	18	...	594	100
1951												
June 15	294	C-2	Measured	60	224	...	...	...	...	...	284	27
		C-2	Computed	62	289	988	570	45	2	...	1960	187
		Contracted	Measured	105	178	766	...	...	...	...	1050	100
July 18	278	C-2	Measured	41	85	190	24	...	...	...	340	38
		C-2	Computed	42	110	397	239	17	1	...	806	90
		Contracted	Measured	72	126	405	261	36	...	...	900	100
Aug. 3	314	C-2	Measured	413	5	98	...	...	...	...	516	33
		C-2	Computed	418	7	242	182	17	1	...	867	56
		Contracted	Measured	328	203	499	468	31	16	16	1560	100
Sep. 6	746	C-2	Measured	4140	816	758	116	...	...	...	5830	58
		C-2	Computed	4190	1040	1960	1220	142	24	13	8590	85
		Contracted	Measured	4140	1010	2220	2320	303	101	...	10100	100
1952												
Apr. 1	1640	C-2	Measured	1013	834	1013	119	...	...	...	2980	40
		C-2	Computed	1020	1030	2240	1140	130	20	11	5590	75
		Contracted	Measured	963	1410	2890	2000	148	...	...	7410	100
May 8	752	C-2	Measured	214	338	231	41	...	...	...	824	41
		C-2	Computed	216	436	617	382	39	3	1	1690	83
		Contracted	Measured	284	304	832	568	41	...	...	2030	100
June 19	262	C-2	Measured	46	39	64	15	...	...	...	164	35
		C-2	Computed	46	53	186	124	11	...	...	420	89
		Contracted	Measured	52	66	212	127	14	...	...	470	100
Sep. 26	255	C-2	Measured	30	36	69	20	...	...	...	155	42
		C-2	Computed	30	47	188	136	13	1	...	415	112
		Contracted	Measured	33	52	178	100	7	...	...	370	100

TABLE 1—*Continued*

Date	Water discharge	Section	Type of sediment discharge	Sediment discharge in tons per day								Percentage of sediment discharge at the contracted section
				Finer than 0.062 mm	0.062 to 0.125 mm	0.125 to 0.25 mm	0.25 to 0.50 mm	0.50 to 1.00 mm	1.00 to 2.00 mm	2.00 to 8.00 mm	Total	
1953	cfs											
May 20	596	C-2	Measured	193	250	162	19	...	...	...	624	41
		C-2	Computed	193	329	513	419	53	5	...	1510	100
		Contracted	Measured	182	362	589	347	30	...	...	1510	100
1951												
July 18	294	C-6	Measured	42	21	201	...	...	...	...	264	28
		C-6	Computed	43	28	425	285	39	2	...	822	86
		Contracted	Measured	77	134	433	278	38	...	...	960	100
Aug. 3	314	C-6	Measured	206	159	223	...	...	...	...	588	36
		C-6	Computed	212	202	515	371	58	5	...	1360	83
		Contracted	Measured	344	213	525	492	33	16	16	1640	100
Sep. 6	650	C-6	Measured	2910	679	970	291	...	...	...	4850	62
		C-6	Computed	2950	825	1740	875	152	31	8	6580	84
		Contracted	Measured	3220	785	1730	1800	236	78	...	7850	100
1952												
May 8	874	C-6	Measured	189	290	307	68	...	...	...	854	46
		C-6	Computed	192	336	507	256	29	1	...	1320	71
		Contracted	Measured	262	280	767	524	37	...	...	1870	100
June 19	294	C-6	Measured	42	42	63	40	4	...	...	191	42
		C-6	Computed	42	50	128	74	8	...	...	302	66
		Contracted	Measured	51	64	207	124	14	...	...	460	100
Sep. 26	504	C-6	Measured	37	54	186	61	...	...	...	338	79
		C-6	Computed	38	63	297	206	24	1	...	629	146
		Contracted	Measured	39	60	206	116	9	...	...	430	100
1953												
May 20	685	C-6	Measured	168	174	268	60	...	...	...	670	47
		C-6	Computed	168	206	570	427	79	8	1	1460	101
		Contracted	Measured	172	346	562	331	29	...	...	1440	100

is under a highway bridge about 1200 ft downstream from the gaging station (see Fig. 7).

Six cross sections were selected upstream and downstream from the flume, and periodic sediment measurements were made for comparison with measurements at the turbulence flume. The selected cross sections represent different channel shapes that are common to streams in the sandhills of Nebraska. In general, sandhill streams have stream beds and banks mostly of sand and are wide and shallow (see Fig. 4).

Comparisons of computed total sediment discharge at five sections with measured sediment discharge at the turbulence flume are given in Figure 6 and Table 2. Twenty-nine computations of total load ranged from 67 to 151 pct and averaged 110 pct of the measured sediment discharge at the turbulence flume [*Hubbell* and *Matejka*, in preparation].

Niobrara River near Valentine, Nebraska—In November 1950 an investigation was started to determine sediment discharges in and near a contracted channel in the Niobrara River near Valentine. The contracted section was formed about October 1, 1950, when a bluff caved into and constricted the river to a chute about 30 ft wide (see Fig. 8).

Most of the stream bed upstream and downstream from the contracted section is composed of shifting sand, but in places the bed may be scoured down to shale or firm clay.

During the periods November 2–17, 1950, and May 8–July 17, 1951, nearly all the sediment was probably in suspension at the contracted section, although a small amount of sediment may have moved through the contracted section as unmeasured load during May–July 1951 [*Colby, Matejka,* and *Hubbell*, 1953].

Sections *A′* and *C*, two of five normal sections at which periodic sediment discharge measurements were made, were about 500 ft upstream and downstream, respectively, from the contracted section.

Comparisons of the results of computations of total load at sections *A′* and *C* with measured sediment discharges at the contracted section are given in Figure 6 and Table 3. In seven comparisons, the computed total sediment discharge averaged 113 pct of the measured sediment discharges at the contracted section.

TABLE 2 – *Comparison of computed total sediment discharge with measured sediment discharge at the normal sections and the turbulence flume of the Middle Loup River at Dunning, Nebr.*

Date	Water discharge	Section	Type of sediment discharge	Sediment discharge	Percentage of sediment discharge at the turbulence flume
	cfs			tons/day	
1949					
Aug. 25	341	A	Measured	190	25
		A	Computed	503	67
		Turbulence flume	Measured	746	100
Sep. 13	376	A	Measured	524	38
		A	Computed	1220	88
		Turbulence flume	Measured	1390	100
1950					
Mar. 1	472	A	Measured	1820	71
		A	Computed	3420	134
		Turbulence flume	Measured	2550	100
Mar. 21	463	A	Measured	1300	43
		A	Computed	2690	88
		Turbulence flume	Measured	3050	100
Apr. 12	421	A	Measured	915	48
		A	Computed	2260	119
		Turbulence flume	Measured	1890	100
Apr. 25	460	A	Measured	989	45
		A	Computed	2350	106
		Turbulence flume	Measured	2210	100
Oct. 4	344	A	Measured	479	50
		A	Computed	1200	125
		Turbulence flume	Measured	958	100
Nov. 30	382	B	Measured	955	56
		B	Computed	1690	100
		Turbulence flume	Measured	1690	100
1951					
Mar. 14	361	B	Measured	1060	55
		B	Computed	2130	110
		Turbulence flume	Measured	1940	100
1950					
Dec. 14	496	B_1	Measured	971	50
		B_1	Computed	1640	85
		Turbulence flume	Measured	1940	100
1951					
June 4	434	B_1	Measured	647	49
		B_1	Computed	1270	97
		Turbulence flume	Measured	1310	100
June 26	424	B_1	Measured	622	53
		B_1	Computed	1150	99
		Turbulence flume	Measured	1170	100
Aug. 16	350	B_1	Measured	314	43
		B_1	Computed	731	101
		Turbulence flume	Measured	724	100
1952					
May 6	370	B_1	Measured	507	43
		B_1	Computed	1170	99
		Turbulence flume	Measured	1180	100
1950					
Oct. 4	344	C_3	Measured	590	64
		C_3	Computed	1080	117
		Turbulence flume	Measured	920	100
Nov. 30	403	C_3	Measured	887	52
		C_3	Computed	1700	99
		Turbulence flume	Measured	1710	100
Dec. 14	485	C_3	Measured	1520	66
		C_3	Computed	2450	107
		Turbulence flume	Measured	2300	100
1951					
Mar. 14	361	C_3	Measured	1070	58
		C_3	Computed	2370	128
		Turbulence flume	Measured	1850	100
June 4	412	C_3	Measured	666	61
		C_3	Computed	1250	115
		Turbulence flume	Measured	1090	100
June 26	361	C_3	Measured	585	76
		C_3	Computed	1070	139
		Turbulence flume	Measured	767	100
Aug. 16	361	C_3	Measured	493	71
		C_3	Computed	986	142
		Turbulence flume	Measured	692	100
1952					
May 6	367	C_3	Measured	495	47
		C_3	Computed	942	90
		Turbulence flume	Measured	1050	100
1950					
Oct. 4	336	E	Measured	421	47
		E	Computed	813	91
		Turbulence flume	Measured	894	100
Nov. 30	397	E	Measured	830	50
		E	Computed	1900	114
		Turbulence flume	Measured	1670	100
Dec. 14	482	E	Measured	1410	64
		E	Computed	2980	135
		Turbulence flume	Measured	2210	100
1951					
Mar. 14	361	E	Measured	1470	71
		E	Computed	3110	151
		Turbulence flume	Measured	2060	100
June 26	412	E	Measured	387	52
		E	Computed	920	124
		Turbulence flume	Measured	742	100
Aug. 16	364	E	Measured	264	40
		E	Computed	592	91
		Turbulence flume	Measured	653	100
1952					
May 6	376	E	Measured	527	58
		E	Computed	1070	118
		Turbulence flume	Measured	903	100

Fivemile Creek near Riverton and near Shoshoni, Wyoming—In October 1950 a sediment station was established on Fivemile Creek near Riverton. The measuring section is beneath a county bridge that spans the contracted section just upstream from Fivemile Creek Falls.

In August 1952 an artificial contraction was constructed of angular boulders upstream from the sediment-sampling station on Fivemile Creek near Shoshoni.

Periodic measurements were made at the contracted sections and at the normal sections adjacent to the contracted sections. The results of total load computations based on data collected at the normal sections and the comparisons with measured sediment discharges are given in Figure 6 and Table 4. Of six comparisons, the computed total load ranged from 92 to 115 pct and averaged

TABLE 3 – *Comparison of computed total sediment discharge with measured sediment discharge at the normal sections and contracted section of the Niobrara River near Valentine, Nebr.*

Date	Water discharge	Section	Type of sediment discharge	Sediment discharge	Percentage of sediment discharge at the contracted section
	cfs			tons/day	
1951					
May 9	765	A′	Measured	1820	43
		A′	Computed	4850	114
		Contracted	Measured	4250	100
May 23	1050	A′	Measured	1710	33
		A′	Computed	4270	83
		Contracted	Measured	5130	100
June 28	951	A′	Measured	1930	45
		A′	Computed	4580	106
		Contracted	Measured	4320	100
July 17	826	A′	Measured	2190	47
		A′	Computed	5230	113
		Contracted	Measured	4640	100
1950					
Nov. 3	804	C	Measured	2260	55
		C	Computed	5510	134
		Contracted	Measured	4120	100
Nov. 10	616	C	Measured	1660	50
		C	Computed	4010	121
		Contracted	Measured	3320	100
1951					
May 9	774	C	Measured	1580	37
		C	Computed	5090	120
		Contracted	Measured	4250	100

TABLE 4 – *Comparison of computed total sediment discharge with measured sediment discharge at the normal and contracted sections of Fivemile Creek near Riverton and Shoshoni, Wyo.*

Date	Water discharge	Section	Type of sediment discharge	Sediment discharge	Percentage of sediment discharge at the contracted section
Near Riverton					
	cfs			tons/day	
1951					
May 1	71	Normal	Measured	10,200	94
		Normal	Computed	12,400	115
		Contracted	Measured	10,800	100
July 6	157	Normal	Measured	8,260	76
		Normal	Computed	10,900	100
		Contracted	Measured	10,900	100
July 19	179	Normal	Measured	11,600	69
		Normal	Computed	15,400	92
		Contracted	Measured	16,700	100
Aug. 3	174	Normal	Measured	8,460	71
		Normal	Computed	12,700	107
		Contracted	Measured	11,900	100
Near Shoshoni					
1953					
Aug. 12	289	Normal	Measured	5,930	69
		Normal	Computed	8,400	98
		Contracted	Measured	8,550	100
Aug. 27	259	Normal	Measured	3,810	64
		Normal	Computed	6,650	112
		Contracted	Measured	5,940	100

TABLE 5 – *Comparison of computed total sediment discharge with measured sediment discharge at the normal section and contracted section of the Snake River near Burge, Nebr.*

Date	Water discharge	Section	Type of sediment discharge	Sediment discharge	Percentage of sediment discharge at the contracted section
	cfs			tons/day	
1952					
May 9	308	Normal	Measured	430	50
		Normal	Computed	1120	131
		Contracted	Measured	856	100
May 23	372	Normal	Measured	509	44
		Normal	Computed	1210	105
		Contracted	Measured	1150	100
June 20	213	Normal	Measured	243	79
		Normal	Computed	572	186
		Contracted	Measured	308	100
July 3	217	Normal	Measured	238	64
		Normal	Computed	515	138
		Contracted	Measured	372	100

104 pct of the measured sediment discharge at the contracted sections [*Colby, Hembree,* and *Rainwater,* in press].

Snake River near Burge, Nebraska—The sediment sampling station near Burge, Nebraska, is at a contracted section about 1.4 miles upstream from the gaging section. Sediment discharge measurements at the contracted section were begun in April 1948.

Periodic sediment discharge measurements have also been made at a nearby normal section. Comparisons of computed total sediment discharge for the normal section with measured sediment discharge at the contracted section are given in Figure 6 and Table 5. Four comparisons of computed total load ranged from 105 to 186 pct and averaged 140 pct of the measured sediment discharge at the contracted section.

Each computation of total sediment discharge gives a greater discharge than that measured at the contraction. *Hubbell, Matejka,* and *Colby* [1952] have shown that not all the sediment discharge of the stream was measured at the contraction. With increased water discharge, the computed total discharge is more nearly equivalent to that measured at the contraction.

COMPARISON OF COMPUTED TOTAL AND UNMEASURED LOADS

Rio Grande near Bernalillo, New Mexico—In the spring of 1952, a special sedimentation study was started on the Rio Grande near Bernalillo, New Mexico. The object of this study was to determine the total sediment movement and the size distribution.

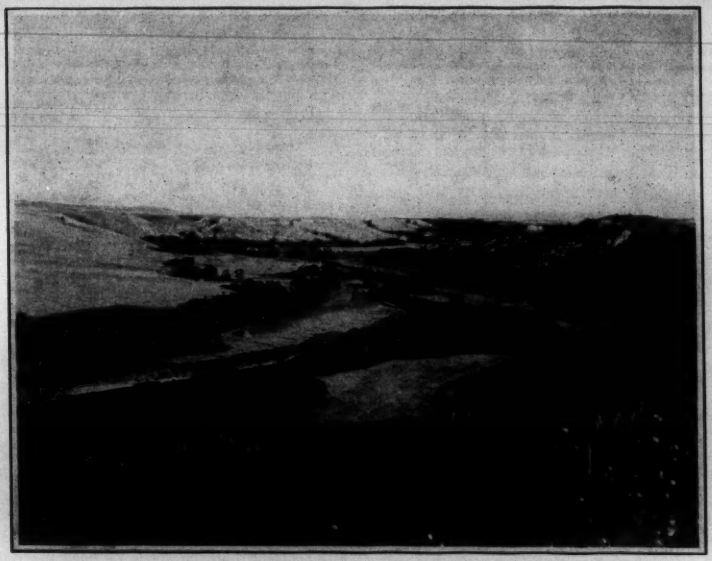

FIG. 4 – Niobrara River near Cody, Nebr.

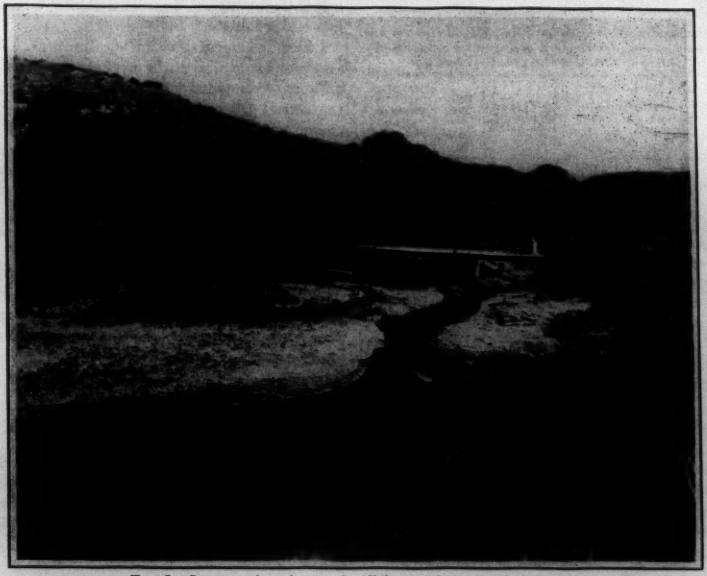

FIG. 5 – Contracted section on the Niobrara River near Cody, Nebr.

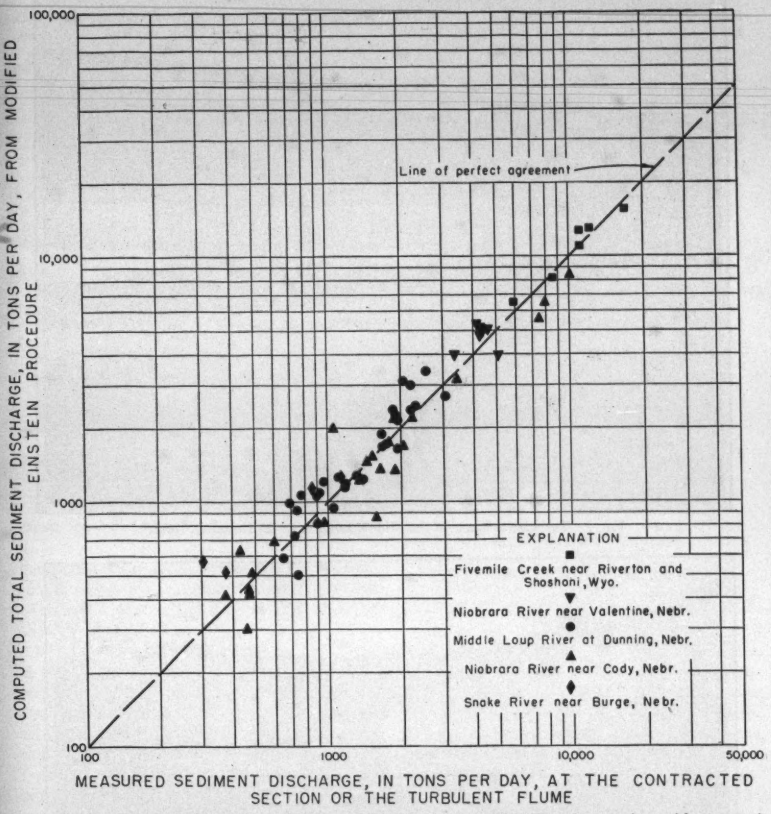
COMPUTED TOTAL SEDIMENT DISCHARGE, IN TONS PER DAY, FROM MODIFIED EINSTEIN PROCEDURE
100,000
10,000
1000
100
100
1000
10,000
50,000
MEASURED SEDIMENT DISCHARGE, IN TONS PER DAY, AT THE CONTRACTED SECTION OR THE TURBULENT FLUME
Line of perfect agreement
EXPLANATION
Fivemile Creek near Riverton and Shoshoni, Wyo.
Niobrara River near Valentine, Nebr.
Middle Loup River at Dunning, Nebr.
Niobrara River near Cody, Nebr.
Snake River near Burge, Nebr.

FIG. 6 – Comparison of computed total sediment discharge from modified Einstein procedure with measured sediment discharge at the contracted section or the turbulent flume

The Rio Grande near Bernalillo is a wide, shallow sandbed stream that transports large quantities of sediment. The water discharge ranges from 3 to 25,000 cfs. A spring rise from mountain snowmelt usually occurs during the period March to July. Low flows prevail during the remainder of the year except for flash floods from storms over the arid parts of the drainage area. The gaging-station section is narrower than the average river width and is a short distance upstream from a tributary arroyo that dumps large quantities of gravel and cobbles into the river. A short distance downstream from the station, the channel is again a wide, shallow alluvial section. As part of the special studies another cableway was installed 8200 ft below the gaging station. The gaging station and lower cableway sections were designated A-2 and F, respectively. Data were collected nearly simultaneously at each section for seven computations of total load by the modified Einstein procedure. The results of the computations at two greatly different widths of the stream are shown in Table 6. The unmeasured load, which is mostly sand, at both sections is appreciable.

Mississippi River at St. Louis, Missouri—In April 1948 a sediment station was established on

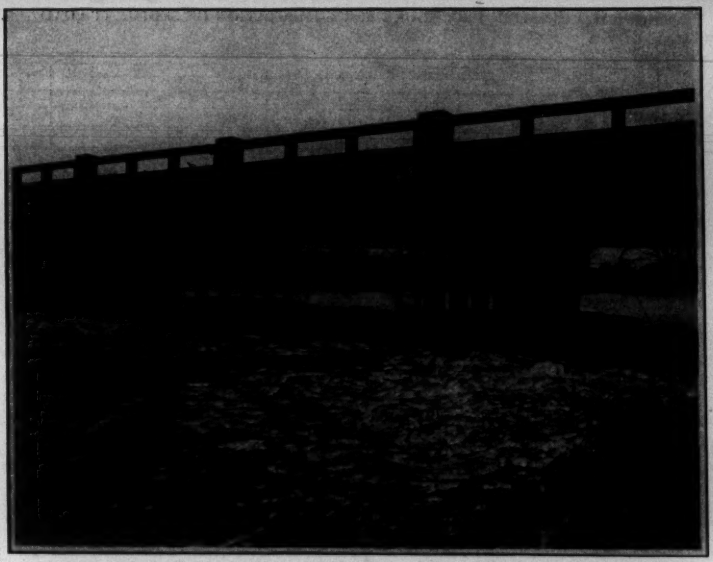

FIG. 7 – Turbulence flume on the Middle Loup River at Dunning, Nebr.

FIG. 8 – Contracted section on the Niobrara River near Valentine, Nebr.

TABLE 6 – *Comparison of total sediment discharge by the modified Einstein procedure between two sections on the Rio Grande River near Bernalillo, N. Mex.*

Date	Water discharge	Section	Sediment discharge		
			Measured	Computed	Ratio of measured to computed
	cfs		tons/day	tons/day	
1952					
Apr. 25	2820	A-2	25,300	37,800	0.67
	2820	F	21,500	40,000	0.54
May 12	6440	A-2	64,500	96,400	0.67
	6440	F	49,400	89,500	0.55
June 17	6120	A-2	39,000	74,500	0.52
	6120	F	28,900	65,500	0.44
June 20	4775	A-2	21,400	39,400	0.54
	4775	F	20,200	45,000	0.45
June 26	2800	A-2	7,120	15,100	0.47
	2800	F	7,150	13,400	0.53
July 24	2030	A-2	15,000	19,400	0.77
	2030	F	10,600	13,000	0.82
1953					
June 2	2150	A-2	11,700	16,000	0.73
	2400	F	12,300	18,000	0.68
Total	...	A-2	...	298,500	...
	...	F	...	284,400	...

Mean width: Sec. A-2, 271 ft; sec. F, 521 ft. Mean depth: Sec. A-3, 3.02 ft; sec. F, 1.90 ft.

TABLE 7 – *Comparison of total sediment discharge computed by the modified Einstein procedure with measured sediment discharge of the Mississippi River at St. Louis, Mo.*

Date	Water discharge	Sediment discharge		
		Measured	Computed	Ratio of measured to computed
	hundred cfs	hundred tons/day	hundred tons/day	
1951				
May 23	3590	18,100	19,200	0.94
July 16	7040	15,900	20,500	0.78
July 22	7630	19,600	23,300	0.84
July 30	4680	11,700	13,800	0.85
Sep. 17	3870	20,400	22,000	0.93
Sep. 26	2400	5,590	5,920	0.94
Oct. 10	2340	5,410	5,570	0.97
Oct. 17	1700	2,740	2,820	0.97
Nov. 13	2190	3,660	3,820	0.96
Dec. 4	2020	2,680	2,940	0.91
1952				
Mar. 17	4110	25,000	28,500	0.88
May 1	6740	16,300	17,100	0.95
June 19	1980	2,820	3,060	0.92
July 9	2100	6,410	7,480	0.86
July 24	1780	4,520	4,720	0.96
Aug. 8	1610	1,300	1,370	0.95
Aug. 19	1670	1,930	2,120	0.91
Sep. 11	1070	1,280	1,290	0.99
Sep. 29	747	540	593	0.91

the Mississippi River at St. Louis. At the gaging-station section the river ranges in width from 1500 to more than 2000 ft and in depth from about 15 to 60 ft.

Nineteen computations of total load for a range of water discharge from 74,700 to 763,000 cfs were made from data collected when periodic sediment discharge measurements were made. The computed total loads ranged from 59,300 to 2,850,000 tons/day. The measured sediment discharges ranged from 78 to 99 pct and averaged 92 pct of the computed total load. The results of the computations are shown in Figure 9 and Table 7. The unsampled depth for the Mississippi River ranged from 0.5 foot to 1.8 ft. Figure 9 is based on results of computations for an unsampled depth of 0.5 foot only.

Niobrara River near Gordon, Nebraska—The Bureau of Reclamation is planning a potential pumping plant to serve irrigable lands in the Lavaca Flats area about eight miles below the Niobrara River near Gordon. As the static pumping head is rather high, the designers are concerned about the large amount of sand, which may cause abrasion to the water passages and working parts of the pump.

The Niobrara River at the gaging station near Gordon is a typical sandhill stream. The water discharge ranges from 35 to 5400 cfs. Sediment data have been collected at this station since 1948. Twenty-six computations of total load were made by the modified Einstein procedure, and the results are presented in Table 8. The computations show that the unmeasured load is a large percentage of the total load. The measured sediment discharge ranged from 7 to 67 pct and averaged 25 pct of the computed total load. A total-load transport curve based on these compilations compares favorably with a transport curve for the contracted section of the Niobrara River near Cody downstream.

Platte River near Overton, Nebraska—From January 1950 to September 1953 sediment discharge measurements were made at the Platte River near Overton. Computed total load for five water discharges from 242 to 4170 cfs ranged from 19 to 3620 tons/day. The measured load ranged from 19 to 95 pct of the computed total load. The results of the computations are shown in Figure 10 and Table 9.

No check is possible at this time on the accuracy of the computed loads. However, for a shallow

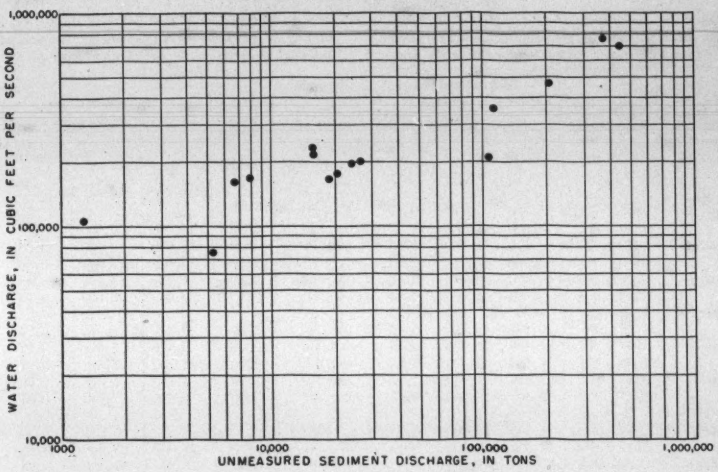

FIG. 9 – Unmeasured sediment discharge plotted against water discharge, Mississippi River at St. Louis, Mo.

stream about 800 ft wide, the computed tonnages appear to be accurate enough for practical use.

Pecos River near Artesia, New Mexico—Special sediment studies were made recently on the Pecos River near Artesia, New Mexico, in conjunction with the planning of a potential channelization project through the McMillan Reservoir delta. The purpose of the channelization is to conserve water, which is now being consumed by the dense growth of phreatophytes. A knowledge of the total sediment load was needed for the design of a stable channel.

The average water discharge at this station is 390 cfs, the maximum computed water discharge is 51,500 cfs, and there is no flow at times. The streamflow is regulated by Alamogordo Reservoir; however, severe flash floods may come from the arid area between Alamogordo and Artesia.

The data from two field observations in the spring of 1954 were used to compute total load by the modified Einstein procedure. The results of the computations are presented in Table 10 and appear to be reasonable. A relatively small sand load is carried by the river at this station.

CONCLUSIONS

In 65 comparisons of total loads computed by the modified procedure with measured loads at sections where we are reasonably sure that total load is measured, the computed loads ranged from 66 to 146 pct of the measured load and averaged 103 pct. Table 11 presents the deviation by percent of the computed total loads from the measured total loads at the six locations where total load has been measured. Nearly two-thirds of the computed loads were within 15 pct of the measured loads and three-quarters were within 20 pct.

The averages in the summary of Table 6 for the two different sections on the Rio Grande near Bernalillo agree within five percent. The maximum difference for the size fractions less than 0.5 mm is 7.4 pct. The differences for the size fractions 0.5 to 1.0 mm and greater than 1.0 mm are 32 and 49 pct, respectively.

The modified Einstein procedure appears to show progress in meeting the objectives of the research studies as previously outlined. Certain functions that have been defined empirically must be defined on a theoretical basis before the procedure can be used on all streams with the expectation of determining accurate total loads.

The field data necessary for computing total loads with the modified Einstein procedure are little more than those collected for the routine sediment and streamflow investigations by the Geological Survey. Normally, one man measures

TABLE 8 - *Comparison of total sediment discharge computed by the modified Einstein procedure with measured sediment discharge of the Niobrara River near Gordon, Nebr.*

Date	Water discharge	Sediment discharge		
		Measured	Computed	Ratio of measured to computed
	cfs	tons/day	tons/day	
1948				
Apr. 13....	138	144	669	0.22
May 7....	115	133	883	0.15
May 17...	105	46	694	0.07
June 4....	103	124	589	0.21
June 24...	157	167	892	0.19
July 20....	185	360	1,190	0.30
Aug. 3....	178	469	3,080	0.15
Sep. 14....	78	26	171	0.15
Sep. 29....	91	38	152	0.25
Oct. 26....	104	79	365	0.22
Nov. 15...	136	156	516	0.30
Dec. 3....	160	256	1,450	0.18
1949				
May 17...	233	482	2,420	0.20
June 17...	135	76	427	0.18
Sep. 13....	104	76	298	0.26
Oct. 28....	107	83	303	0.28
Nov. 17...	114	136	535	0.25
1951				
Mar. 8....	27	28	129	0.22
Mar. 21...	123	107	516	0.21
July 28....	4100	97,000	144,500	0.67
1953				
Feb. 5....	195	252	1,060	0.24
Mar. 4....	134	201	526	0.38
Mar. 11...	235	342	1,610	0.21
Apr. 15....	125	76	510	0.15
July 29....	714	7,630	15,100	0.50
Aug. 18...	89	38	120	0.32

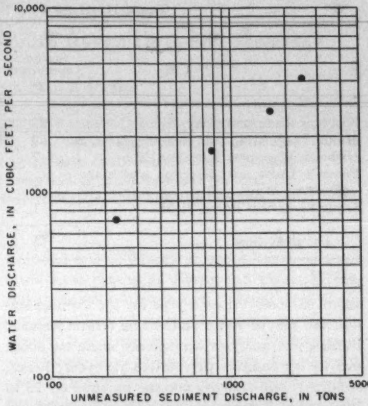

FIG. 10 - Unmeasured sediment discharge plotted against water discharge, Platte River near Overton, Nebr.

TABLE 9 - *Comparison of total sediment discharge computed by the modified Einstein procedure with measured sediment discharge of the Platte River near Overton, Nebr.*

Date	Water discharge	Sediment discharge		
		Measured	Computed	Ratio of measured to computed
	cfs	tons/day	tons/day	
1952				
Apr. 2.....	4170	1140	3620	0.31
May 15...	1680	185	960	0.19
June 12...	2760	1010	2640	0.38
Sep. 25....	702	83	314	0.26
1953				
July 9.....	242	18	19	0.95

sediment and water discharges at an established station. About a half hour to one hour of extra time is required to collect the additional necessary data. The major expenditures for station operation are for equipment and personnel. If the additional data necessary for a modified Einstein computation are obtained as part of the routine investigations, the expenditure is nominal.

Normally, all the suspended-sediment samples are analyzed for concentration and some are analyzed for particle size. Hence, the only additional laboratory work required is analyzing more samples for particle size. Field personnel will make

TABLE 10 - *Comparison of total sediment discharge computed by the modified Einstein procedure with measured sediment discharge of the Pecos River near Artesia, N. Mex.*

Date	Water discharge	Sediment discharge		
		Measured	Computed	Ratio of measured to computed
	cfs	tons/day	tons/day	
1954				
Apr. 9.....	717	8700	9420	0.92
Apr. 15....	920	8050	9310	0.86

TABLE 11 – *Accuracy of the modified Einstein procedure*

Station	Number of comparisons	Percentage probability of agreement of computed and measured total load					
		Within 5 pct	Within 10 pct	Within 15 pct	Within 20 pct	Within 25 pct	Within 30 pct
Niobrara River near Cody, Nebr.	22	23	41	68	82	86	91
Middle Loup River near Dunning, Nebr.	29	21	41	59	69	76	79
Niobrara River near Valentine, Nebr.	7	0	14	43	71	86	86
Fivemile Creek near Riverton and near Shoshoni, Wyo.	6	33	67	100	...	...	...
Snake River near Burge, Nebr.	1	100	...	...	...	...	...
For all stations	65	22	42	65	77	83	86

about 20 observations a year for the average station and maybe 40 for stations on erratic streams. Particle-size analyses are usually made on about five to ten samples per station per year; hence, additional size analysis may be required on 15 to 35 samples. Particle-size analysis of bed material may be required for 50 or more samples per station per year.

Forms have been developed by both the Bureau of Reclamation and the Geological Survey for an orderly and documented step computation of the modified Einstein procedure. After a short training period a beginning engineer can complete a computation in two hours or less.

The amount of total load data required for projects on different streams varies. For most of the projects of the Bureau of Reclamation, 20 to 25 total-load computations that adequately covered the range in river stage have been sufficient. The modified Einstein procedure is the most accurate and economical method that has been used by the Bureau.

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Rayleigh Wave Dispersion in the Period Range 10 to 500 Seconds*

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Abstract—A composite Rayleigh wave dispersion curve obtained from earthquake seismograms is presented for the period range 10–500 sec. For periods greater than 75 sec the dispersion is primarily influenced by the shear velocity gradient in the mantle. For periods less than 75 sec the effect of the crustal layer is most important. Brief discussions of the spectrum of the initial impulse and stationary values of group velocity, as they influence the character of seismograms, are given.

Introduction—With the placement of long-period vertical seismographs at a few very carefully selected stations, Palisades, Bermuda, Pietermaritzburg, and Perth, observations of Rayleigh wave dispersion have improved in precision and completeness. In this paper we present a composite Rayleigh wave dispersion curve covering the period range 10–500 sec.

For periods greater than 75 sec a single dispersion curve occurs, that for mantle Rayleigh waves. For these long periods the dispersion is influenced primarily by the variation of shear velocity with depth in the mantle.

For periods less than 75 sec crustal Rayleigh waves occur in which the dispersion is primarily influenced by velocity variations within the crust, and by the velocity contrast at the Mohorovicic discontinuity, it being possible to consider their theory with good approximation by treating the mantle velocity as constant with depth. For periods less than 75 sec the dispersion of Rayleigh waves along continental paths is increasingly different from that along oceanic paths. Hence the crustal Rayleigh wave dispersion divides into two parts at 75 sec.

The scarcity of data in the past is because of the fact that good observations of oceanic Rayleigh waves can be obtained only by stations situated on islands or on the coastlines of continents, and continental Rayleigh waves only at stations where long, purely continental paths are available to reasonably active earthquake belts. Mantle waves can be studied wherever long-period seismographs, particularly vertical components, are available but the limitation imposed in this case is that only the greatest earthquakes produce them.

The composite dispersion curve—In Figure 1 we present the composite dispersion curve. It is divided by a vertical dashed line at about 75-sec period into crustal Rayleigh waves and mantle Rayleigh waves. Mantle Rayleigh wave data are taken from papers by *Ewing* and *Press* [1954ab] and are based in large part on observation of period and travel time of waves which have traveled unusually large distances, up to about 300,000 km or about seven times around the Earth. At a period of about 75 sec the group velocity is about 3.9 km/sec. For periods between about 75 sec and 225 sec, the group velocity decreases gradually with increasing period, to a minimum value of about 3.5 km/sec at 225 sec. Beyond this, to about 400 sec, the group velocity increases more rapidly, apparently reaching a maximum of about 4.1 km/sec at about 400 sec. The division between mantle and crustal Rayleigh waves is characterized by two closely related phenomena. It is the point at which the dispersion curves for continental and oceanic Rayleigh waves begin to diverge as the period shortens, hence it marks the short-period limit of efficient energy transmission on paths which repeatedly cross continental borders. In addition, this division occurs near the period of maximum group velocity for continental paths.

Oceanic crustal Rayleigh waves have been discussed in several papers [*Ewing* and *Press*, 1952; *Oliver*, *Ewing*, and *Press*, 1955] and it has been demonstrated that the dispersion is greatly influenced by the presence of the water layer in the ocean. In fact, a rather satisfactory approximate theory can be made by considering the propagation in a system consisting of a water layer overlying a homogenous solid substratum. Oceanic Rayleigh waves have been observed with velocities ranging approximately from 4.0 km/sec to 1.4 km/sec. The steepness of the group-velocity curve for the lower velocities accounts for the almost sinusoidal trains of waves, of remarkably long duration, which have usually been referred to as the codas of distant earthquakes. Although the simple theory referred to above predicts a minimum group velocity at a period of about 15 sec, with a rise to the speed of sound in water for shorter periods, we have never observed waves corresponding to this part of the

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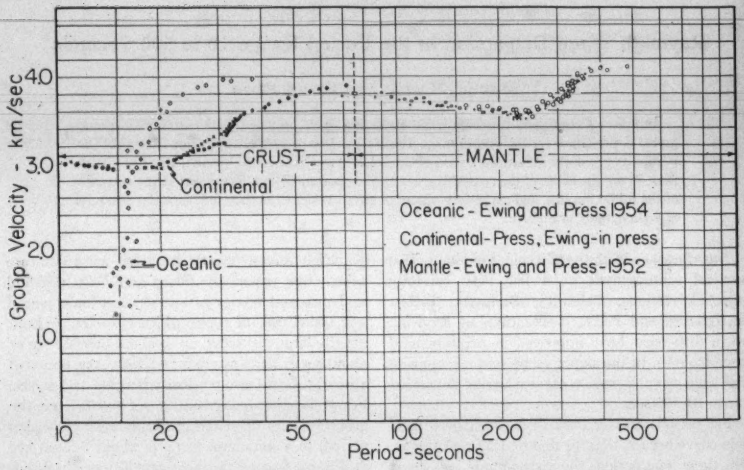

FIG. 1 – Observed dispersion of Rayleigh waves in the period range of 10 to 500 seconds

dispersion curve despite careful searches for it. The explanation of this important discrepancy is being sought. Crustal structure over oceanic areas, even including such detail as the thickness of the sedimentary layer, has been deduced from oceanic dispersion curves and found to be in excellent agreement with the results of seismic refraction measurements at sea [*Press* and *Ewing*, 1955]. The maximum group velocity for oceanic Rayleigh waves appears to lie between 30 and 40 sec period at about 4 km/sec, a higher velocity and a shorter period than that for the continental crustal waves. The gap in data from 40 to 70 sec for oceanic Rayleigh wave dispersion occurs because we have not yet had sufficiently long paths to long period seismometers, with clear oceanic crust over the entire path.

The continental crustal Rayleigh wave dispersion curve shows a far smaller range of group velocities than the oceanic one. For this reason it requires a very long, purely continental path to obtain good dispersion data for it, and until very recently such data have not been available. The curve shown is based primarily on two investigations, one for North America [*Brilliant* and *Ewing*, 1954] and one for Africa [*Press*, *Ewing*, and *Oliver*, in press]. Although the North American data cover a far smaller period range, it was possible to get precision velocities by the use of waves from a composite path, recorded by a succession of stations along a continental segment of that path. The African data, however, are very complete, covering a purely continental path free from obvious crustal anomalies, about 8000 km in length. The existence of a minimum group velocity at slightly less than 3 km/sec, for periods of about 16–18 sec, is clearly demonstrated, with inverse dispersion evident on the short-period side of this minimum, and direct dispersion visible on the long-period side. The maximum of group velocity for continental crustal Rayleigh waves is, as mentioned before, at about 3.9 km/sec for periods of about 75 sec.

Spectrum of initial impulse and qualities of seismograms—In principle, any earthquake impulse should contain spectral components covering the entire range of frequencies, and it should be possible to observe waves corresponding to this composite dispersion curve from any shock. In practice, however, it is found that only some shocks of magnitude $7\frac{3}{4}$ or greater excite the mantle Rayleigh waves. A tentative suggestion is made that the motion at the focus of those earthquakes which excite mantle Rayleigh waves has a higher content of long-period energy than for other shocks of similar size.

For crustal Rayleigh waves of both continental and oceanic types it is approximately true that all earthquakes excite the whole spectrum to a measurable extent. However, it is possible to make an arbitrary division of the spectral range at about 15

sec and to state that some earthquakes excite periods shorter than this value much more strongly than they do periods longer than this value, or vice versa.

The wide variations in general appearance of seismograms can be very largely accounted for by two of the factors mentioned above. One is the continental or oceanic character of the propagation paths, and the other is the relative excitation of high or low frequency surface waves, controlled by depth of focus and spectrum of the motion at the focus.

Stationary values of group velocities—It is well known that for suitably large propagation distances, large-amplitude waves are associated with stationary values of group velocity, since the slope of the group velocity curve occurs in the denominator of the functions giving the amplitude of the waves. This effect has been observed and described for the minimum group velocity of mantle Rayleigh waves [*Ewing* and *Press*, 1954ab]. The minimum corresponding to continental crustal Rayleigh waves has also been observed, although not with predominantly large amplitudes, due to the limitation in available path length. As mentioned above, the minimum group velocity for oceanic Rayleigh waves is complicated by some factor yet to be identified.

Maxima of group velocity are of more significance for general studies of seismograms than minima, since they initiate trains of waves and are inherently easier to identify. The presence of the broad maximum of group velocity for continental Rayleigh waves implies that these waves should be initiated by a sharp, almost impulsive beginning, an effect which is difficult to observe because of the rapidly decreasing response of seismographs as the wave periods rise to about 70 sec, and the necessity for a very long continental path. However, in the few well-suited records that are available there is a suggestion on the seismograms that this effect is present. As mentioned above, the maximum group velocity for oceanic crustal Rayleigh waves is at a shorter period. Again there is an indication on the seismograms that an abrupt beginning of the Rayleigh wave train is associated with this maximum.

The Rg phase [*Press, Ewing*, and *Oliver*, in press] has definitely been associated with the short-period limit of 10 sec at about 3.0 km/sec group velocity of the curve shown in Figure 1. We infer from the striking impulsive character of the beginning of Rg in suitable cases that the maximum which occurs at this point is real and is associated with velocity gradients within the crust. Since the short-period limit for Rayleigh waves in a simple granitic crust is about 3.2 km/sec, we infer that between 10-sec period and 0-sec period there is at least one additional minimum of the Rayleigh-wave group velocity which has not yet been observed, and that this minimum is associated with layering which is definite and reasonably constant over paths whose lengths reach continental dimensions.

As stated above, the maximum in group velocity for mantle Rayleigh waves at about 400-sec period is indicated but has not yet been completely demonstrated by adequate data. We believe that this maximum is produced by the liquid core. In other words, the wave lengths here are about 2000 km, and at this length they begin to be affected by the vanishing rigidity of the core. Longer-period instruments intended for observing the dispersion of Rayleigh waves with periods greater than 500 sec are under construction, and it is expected that this part of the dispersion curve will be available in the near future.

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On the Isotopic Constitution of Radium (Ra-224/Ra-226 and Ra-228/Ra-226) in Petroleum Brines

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Abstract—The relative amounts of Ra-224, Ra-226, and Ra-228 in a number of petroleum brine samples from Oklahoma and northwestern Arkansas have been determined. The highest concentration found was more than one millimicrocurie/liter of brine. Some brines contained radium isotopes characteristic of the thorium series, others contained Ra-226 which is characteristic of the uranium series, while others contained radium from both the thorium and uranium series. The radium isotopes in the brines are not in radioactive equilibrium with their uranium and thorium parents.

It has recently been shown by one of the authors [*Kuroda*, 1955; in preparation] that the isotopic constitution of radium (RA-223/Ra-226) in uranium minerals shows fluctuations presumably caused by the non-equilibrium relationship between uranium and radium isotopes. Similar techniques have been used by the authors to investigate the complicated equilibria between radium isotopes (Ra-224, Ra-226, Ra-228) and their parent and daughter elements in brines and scales associated with petroleum from Oklahoma and northwestern Arkansas. The preliminary results are presented in this paper.

It has long been known that the brines associated with petroleum show unusually high concentrations of radium isotopes and extensive works were made in the USSR in the 1930's [*Kuroda*, 1953]. A preliminary study on the equilibria between MsTh 1 (Ra-228), RdTh (Th-228), and ThX (Ra-224) in petroleum brines was made by Bobin [1933].

Komlev [1933] and *Nikitin* [1933] showed that radium-bearing waters contain considerable quantities of alkaline earth metals and practically no sulfates.

Studies on the radium isotopes (Ra-223, Ra-224, Ra-226 and Ra-228) in brine type hot spring waters in Japan were made by *Kuroda* and *Yokoyama* [1948, 1949, 1953] in the 1940's. The equilibrium relationship between Ra-228, Th-228, and Ra-224 was found to be very similar to that in the petroleum brines studied by Bobin. *Yokoyama* and *Yokoyama* [in preparation] have recently made a calculation and showed that the relative amounts of Ra-224, Ra-226 and Ra-228 in hot spring waters can be explained by the leaching of these isotopes from the underground deposits enriched in their parent elements.

Gott and *Hill* [1953] reported that the brines and scales from the petroleum wells in southern Kansas contain appreciable amounts of Ra-226, although the uranium content is much less than that expected from the equilibrium between uranium and radium. The radium isotopes from the thorium series decay chains (Ra-224 and Ra-228) were not investigated by Gott and Hill. *Stehney* [1953] has recently published a paper on radium (Ra-226) and thorium X (Ra-224) in some potable waters.

Experimental Procedure

Apparatus—An end-window Geiger counter (3 mg cm^{-2}) was used for the beta-radioactivity measurements. An IM-type fontactoscope [*Kuroda* and *Yokoyama*, 1953] was used in the field for the determination of radon in natural gas and brine samples.

Determination of the relative amounts of Ra-224, Ra-226, and Ra-228—The isotopes of radium were co-precipitated with barium as sulfate from 0.5 to 10 liters of brine samples. The amount of brine sample was adjusted so that approximately one millimicrocurie of radium isotopes would finally be obtained. Since appreciable amounts of barium are usually found in brines, the amount of barium carrier to be added to the sample was adjusted so that the radium isotopes were finally extracted on about 150 mg of barium sulfate. The barium sulfate precipitate was filtered, dried, ignited, and then fused with 0.5 grams of anhydrous sodium carbonate in a platinum crucible. The melt was extracted with hot water and the residue removed by filtration. This residue was dissolved in a small volume of dilute hydrochloric acid. One ml of lanthanum nitrate solution (10 mg per ml) was added to the hydrochloric acid solution and lanthanum hydroxide precipitated by the addition of ammonium hydroxide. (Commercial lanthanum generally carries a small amount of activity. The lanthanum nitrate solution used by the authors was free from Ra-224, Ra-226 and Ra-228, but contained 0.5 cpm of Ra-223 per ml.) The solution was boiled for one minute and then filtered. Another one ml portion of the lanthanum nitrate solution was

added to the filtrate and the precipitate of lanthanum hydroxide was again removed by filtration. Barium was finally precipitated as carbonate by the addition of ammonium carbonate, filtered through a Gooch crucible (S&S analytical filter paper 895-E, 21 m/m), dried, and mounted on a planchette. The sample was counted for about four weeks and a growth-decay curve due to Ra-224 + Ra-226 + Ra-228 was obtained. The sample was then dissolved in hydrochloric acid and the procedure of the addition and removal of lanthanum was repeated, and barium was again precipitated as the carbonate. The barium carbonate precipitate was filtered off, dried, mounted on a planchette, and counted for another four weeks to obtain the growth curve due to Ra-226 + Ra-228.

From the two growth(-decay) curves, the relative amounts of Ra-224, Ra-226 and Ra-228 were calculated. The loss of radium isotopes during the purification procedure was usually 15 ± 5 pct.

Determination of Ra-226—The Ra-226 contents of brine samples were determined by either the standard Ra-226 addition method or the Rn-222 method described below.

TABLE 1 – *Increase of radon content of brine after the sampling*

Sample	Time after sampling	Radon content
	day	*millimicrocuries/liter*
BA-2	1.2	0.128
	3.4	0.212
	7.0	0.345
	16.0	0.460
	22.0	0.480
BA-3	1.25	0.655
	2.0	0.881
	7.0	1.39
	21.0	1.53
	30.0	1.55

Standard Ra-226 addition method: The ratios of Ra-224/Ra-226 or Ra-228/Ra-226 or both in the same brine sample were determined with and without addition of a known amount of U.S. Bureau of Standards' Ra-226 standard solution (for example, 0.500 millimicrograms Ra-226 to 500 ml of brine), and the actual concentration of Ra-226 in the brine sample was calculated from these ratios.

Rn-222 method: The radon content of the brine sample was determined several times during a period of three or four weeks after the sample was taken, and from the radon content of the brine sample when the equilibrium was reached between radium and radon, the Ra-226 content of the sample was obtained. The Ra-226 content of BA-3 was found to be 1.62 ± 0.06 millimicrograms per liter by the standard Ra-226 addition method, whereas the Rn-222 method gave 1.55 millimicrograms per liter (see Tables 1 and 2).

Determination of Ra-224 and Ra-228—The Ra-224 and Ra-228 contents of brine samples can be obtained from their Ra-226 contents and the relative amounts of Ra-224, Ra-226, and Ra-228. However, the Geiger counter should be calibrated against the known amounts of Ra-224, Ra-226 and Ra-228, since the energies of the beta-particles from various decay products of radium isotopes are different.

Since an old thorium salt was not available in this laboratory, a thorite (var. uranothorite from Tvedstrand, Norway), which contained 40.70 pct ThO_2 and 3.52 pct U_3O_8 was used as a standard. The Ra-226 content of this mineral was calculated to be 10.1 millimicrograms per gram and the Ra-224 content to be 42.3 millimicrocuries per gram (the Ra-228 content is the same as that of Ra-224 in terms of curies per gram). The radium isotopes were isolated with barium sulfate carrier (150 mg) from 100 mg of thorite, with and without

TABLE 2 – *Radium isotopes in brines (in millimicrocuries per liter)*

Sample	Location	Ra-224	Ra-226	Ra-228
PK-1	North Burbank, Okla.	0.27 ±0.03	0.05 ±0.05	—[a]
PK-2	North Burbank, Okla.	0.13 ±0.01	0.01 ±0.01	—[a]
PK-3	North Burbank, Okla.	0.18 ±0.02	0.01 ±0.01	0.16 ±0.02
PK-4	North Burbank, Okla.	0.29 ±0.03	0.58 ±0.06	—[a]
PK-5	North Burbank, Okla.	0.08 ±0.01	0.01 ±0.01	—[a]
PK-6	South Burbank, Okla.	1.09 ±0.10	0.60 ±0.06	—[a]
PK-7	Claremore Radium Springs, Okla.	—[a]	0.57 ±0.06	—[a]
BA-1	Ella, Okla.	—[a]	0.70 ±0.07	—[a]
BA-2	Medrano, Okla.	—[a]	0.48 ±0.05	0.24 ±0.02
BA-3	Rowe, Okla.	0.10 ±0.01	1.62 ±0.06	0.40 ±0.04
BA-4	Huggins, Ark.	—[a]	0.001 ±0.001	0.075 ±0.008

[a] —Indicates that the measurement has not been made.

TABLE 3 – *Calibration of Geiger counter; number of counts obtained with 1.00 millimicrocurie of Ra-224, Ra-226 and Ra-228 in 150 mg of barium sulfate*

Specimen	cpm
$I_{Ra\text{-}224,\ t=0}$	493 ±10
$I_{Ra\text{-}226,\ t=30d}$	643 ±10
$I_{Ra\text{-}228,\ t=30d}$	430 ±10

addition of one millimicrogram of U.S. Bureau of Standards' Ra-226, and the relative amounts of radium isotopes were determined according to the method previously described. From the decay curves obtained, the radioactivity due to Ra-224 and its daughters extrapolated to the time of barium separation, $I_{Ra\text{-}224,\ t=0}$, and the radioactivity due to Ra-228 and its daughter 30 days after the barium separation, $I_{Ra\text{-}228,\ t=30d}$, was calculated. These values expressed in terms of 1.00 millimicrocuries for each isotope and corrected for yield losses in processing, are shown in Table 3.

Determination of RdTh(Th-228) and RdAc(Th-227)—The isotopes of thorium were co-precipitated with ferric hydroxide from ten liters of brine sample, after the radium isotopes had been removed with barium sulfate. (There was enough iron present in most brine samples so that the addition of iron carrier was unnecessary.) The precipitate of ferric hydroxide was dissolved in dilute hydrochloric acid and the addition and removal of barium carrier as sulfate was repeated until the last trace of radium isotopes was removed from the iron fraction. The iron solution was then stored for about a month to allow Ra-224 and Ra-223 to grow in from Th-228 and Th-227, respectively. The radium isotopes formed during this period were co-precipitated with barium carrier and the barium precipitate was purified as described previously. A growth-decay curve due to Ra-223 (11.2 days) and Ra-224 (3.64 days) was obtained and the amounts of Th-227 and Th-228 are calculated from the amounts of Ra-223 and Ra-224 found.

EXPERIMENTAL RESULTS AND DISCUSSION

The radon content of a number of natural gas samples associated with brines and petroleums in the central Oklahoma and northwestern Arkansas areas was found to be, in general, low. Gas samples from eight wells in the Oklahoma oil fields gave 5.4, 6.2, 6.9, 7.4, 7.4, 3.2, 6.4, and 3.2 micromicrocuries of Rn-222 per liter of gas, while samples from three natural gas wells in the northwestern Arkansas area gave 8.2, 18.5, and 16.5 micromicrocuries of Rn-222 per liter of gas. Nine of the wells tested were in full production at the time of sampling and all showed less than ten micromicrocuries of Rn-222 per liter of gas. However, the two wells which showed more than ten micromicrocuries of Rn-222 per liter of gas had not been in production for three months prior to the time of sampling.

Usually, radium and radon are not in equilibrium (a deficiency of radon) in brines at the time of sampling. This is probably caused by the loss of radon from brines due to mechanical agitation.

The radon content of two brine samples from central Oklahoma (BA-2, Medrano; BA-3, Rowe) was measured several times during the four weeks following the sampling and an increase of radon (the growing in of Rn-222 from Ra-226) contents was observed as shown in Table 1.

The relative amounts of Ra-224, Ra-226, and Ra-228 in a number of brine samples were measured and showed typical growth curves of thorium series radium isotopes. Figure 1 shows the growth curves obtained with PK-3 (North Burbank, Oklahoma), together with a growth curve (Curve I) obtained with thorium nitrate. Curve II (the barium sulfate separation was made three days after sampling) shows a maximum due to Ra-224, whereas Curve III (the barium sulfate separation was made more than 30 days after sampling) shows a growth curve similar to that of Ra-228. These results indicate that the Ra-224 in brine is not supported by its parent, Th-228 (1.90 years). The Ra-224, Ra-226 and Ra-228 contents of a number of brine samples investigated are shown in Table 2.

The Th-228 and Th-227 contents of BA-3 were estimated using ten liters of the brine sample. The Th-228 content was found to be 0.008 ± 0.002 millimicrocuries per liter and the Th-227 content was found to be less than 0.0005 millimicrocuries per liter. The Th-228/Ra-228 ratio in BA-3 is then about two per cent of the equilibrium value and the Th-228/Ra-224 ratio is about eight per cent of the equilibrium value. The absence of Th-227 (18.9 days) in brine indicates the absence of Ac-227 (21 years). The Ac-227 content of BA-3 was thus estimated to be less than 0.0005 millimicrocuries per liter.

Shimokata [in preparation] has recently reported the thorium content in 102 samples of hot springs in Japan. The method used by Shimokata involves the determination of the thoron (Rn-220) which is in equilibrium with Th-228, and it is assumed that Th-228 and Th-232 are in equilibrium in water. If the equilibrium between Th-232 and Th-228 is

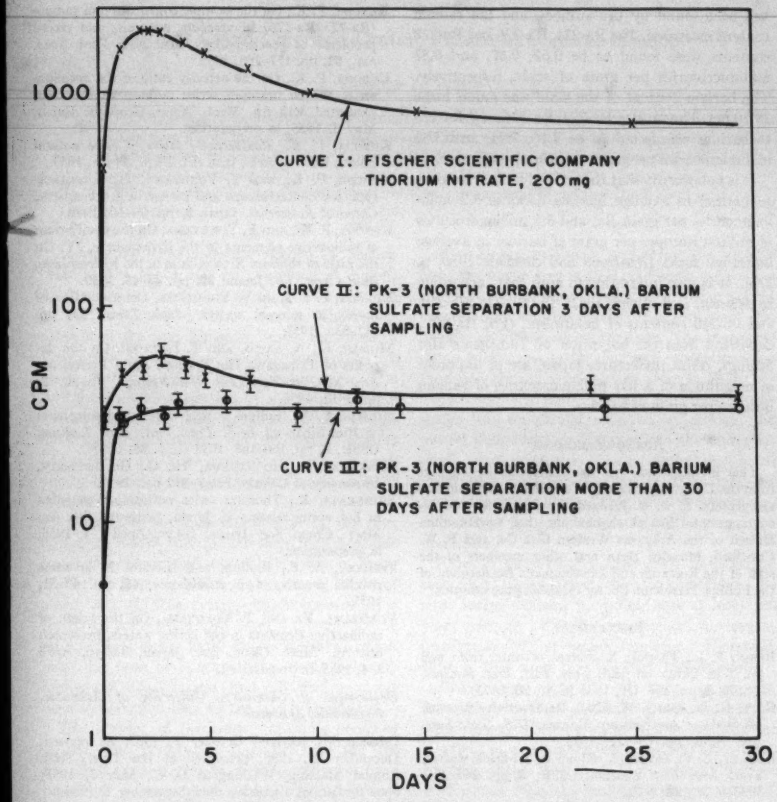

FIG. 1 – Growth curves caused by thorium series of radio isotopes

assumed in brine, the Th-228 content will give the Th-232 content of the brine. Thus, the Th-232 content of BA-3 is 0.008 ± 0.002 millimicrocuries per liter, or 7.0 ± 1.8 × 10^{-6} grams Th-232 per liter.

If it is assumed that Ra-224 and Ra-228 were in equilibrium at the time when the brine leached the radium isotopes from thorium-bearing materials, the Ra-224/Ra-228 ratio at the time of sampling will give the time elapsed since the brine was last in contact with such thorium-bearing materials under the ground. Simple calculations give a value of 175 ± 18 hours.

The upper limit for the Ac-227 content of the brine will also be useful in estimating the approximate U-238 content of the brine. Assuming that the Ac-227/U-238 ratio is 0.046 (curie/curie) and is valid in the brine, the upper limit of the U-238 content of BA-3 is found to be approximately 0.01 millimicrocuries per liter, or 3 × 10^{-6} grams of U-238 per liter.

Gott and *Hill* [1953] found that the radium (Ra-226) content of scales from the petroleum wells in southern Kansas reaches ten millimicrocuries per gram of scale, or more. They reported the radioactivity is almost entirely due to Ra-226 and its decay products, with the equivalent amount of U-238 being absent. A similar barium sulfate scale

has been found by the authors, and the radium content measured. The Ra-224, Ra-226 and Ra-228 contents were found to be 0.62, 0.67, and 0.87 millimicrocuries per gram of scale, respectively. The barium content of the scale was found to be 28.70 pct. The ratio of Ra-224, Ra-226, and Ra-228 to barium was found to be 2.16, 2.34, and 3.03 millimicrocuries per gram of barium, respectively.

It is noteworthy that the ratio of radium isotopes to barium in average igneous rocks is 5.2 millimicrocuries per gram Ba, and 3.5 millimicrocuries of radium isotopes per gram of barium in average limestone rocks [*Rankama* and *Sahama*, 1950, p. 226]. It is also interesting to note that, according to *Minami* and others [1952], the Ra-226, Pb-210, and Po-210 contents of hokutolite, (Pb, Ba)SO_4, deposited from the hot water of Tamagawa Hot Springs, Akita prefecture, Japan, are of the order of magnitude of a few millimicrocuries of radium isotopes per gram of barium.

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Age of Cerro Colorado Crater, Pinacate, Sonora, Mexico

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Abstract—Cerro Colorado Crater, a prominent landmark at Pinacate, Sonora, Mexico, has a minimum age of about 150 years, as determined from physiographic evidence; a geologic age not greater than that of the most recent ash falls at Pinacate; and an archaeological age probably not exceeding 1000 years, as indicated by pottery shards included in these ash beds. Lack of mention of Cerro Colorado Crater in Kino's descriptions of the area (1698–1706) is most puzzling.

Introduction—The Pinacate Region of Sonora (Fig. 1) lies about 100 mi southeast of Yuma, Arizona; 25 mi west of Sonoyta, Sonora; and 30 mi north of Puerto Peñasco, Sonora. The region consists of the four Pinacate Peaks, remnants of Pleistocene Santa Clara Volcano, surrounded by about 1500 sq mi of hard basaltic lava. The lava flows are characterized by a number of spectacular pit craters (called calderas locally and in most published accounts) and by myriad spatter and cinder cones. Some parts of the lava are overlain by laminated deposits of volcanic ash, up to 20 ft in thickness.

Separated from the eastern edge of the lava flows by a belt of volcanic ash there rises a reddish crater of volcanic mud, about half a mile in diameter at the base, and having a maximum height of about 300 ft. This crater, which appears as a truncated cone when seen from a distance, is 18 mi northeast of the main Pinacate Peaks and almost due west of Sonoyta (Fig. 2). It is locally known as Cerro Colorado (Red Hill), and may have been so named in 1907 by the late J. D. Milton.

The interior of the crater, which is breached on the west, is about 50 ft higher than the surrounding exterior terrain. Crater walls are composed of volcanic mud, which superficially resembles hard red sandstone, but which is extremely friable, and which disintegrates rapidly when wet. Crater material weathers from red to a dirty yellow in a few years, and to a grayish white in a few decades. Bentonitic material fills depressions in the outwash plain surrounding the crater, and is irregularly distributed through the crater walls.

Historical changes in the crater—First clear description of Cerro Colorado crater was written by *Hornaday* [1908, pp. 138–141]. A competent map of the area was made at the same time by Godfrey Sykes. Independent observations two years later, by *Lumholtz* [1912, pp. 203–204] and Alberto Celaya, confirm Hornaday's descriptions.

After Hornaday's visit, and before the writer's first visit to the area in 1931, the north wall of the crater interior slumped, losing two wedge-shaped masses, each approximately 1000 feet long, 100 ft high, and 20 ft across the base. The innermost slump wedge was badly shattered, and about one third had already been washed away in 1931.

Between 1931 and 1954, the innermost slump wedge was completely removed by erosion, the second wedge had slid further into the crater interior, and additional cracks along the north crater wall, both interior and exterior, indicated another incipient slump. This, when it takes place, will change the exterior profile of the crater appreciably.

Rates of gully cutting, from 1907 to 1954, are such that, under desert climatic conditions, the most recent date of 'no gullies' was at least 100 years prior to 1907. In consequence, the crater, despite its "air of recent formation" [*Lumholtz*, 1912, p. 203], must be more than 150 years old.

Stratigraphic relations—Ash beds occur under the wash from Cerro Colorado crater, but are not interfingered with the wash. These ash beds are identical in appearance, composition, and stratigraphic position with those 15 mi away at the foot of the main Pinacate Peaks. Wash from the two exposures of ash interfingers in the bed of the Sonoyta River east of the lava flows. In consequence, Cerro Colorado crater is not older than the major ash deposits, which are, in turn, younger than any major lava flow at Pinacate.

Archaeological evidence—Contained in the volcanic ash at Tinaja de Emilia and at Papago Tanks [*Lumholtz*, 1912, map in pocket] are pottery shards, indistinguishable from undeniably modern Papago pottery except for a slight caliche induration. Best present evidence, in part supported by tree-ring and radiocarbon datings from other areas, is that this general type of pottery is not over 1000 years old.

Description of the ash-producing eruption may

FIG. 1 – Summary outline map of southwestern North America, showing location of Pinacate Region

be contained in a Papago legend, which tells of a lowering of the Pinacate Peaks by an eruption, with a rain of volcanic ash "covering the country" [*Lumholtz*, 1912, p. 203; *Ives*, 1935].

Questioning of modern Papago Indians produced the information that this eruption occurred after the flood (another legend), and before the time of Padre Kino (1698), but not long before. Whether the term 'not long' refers to ten days or ten generations, the informants do not know.

Historical investigation—Because Cerro Colorado crater is a prominent landmark on the east flank of the Pinacate lava fields, which were adjacent to old Spanish trails used as long ago as 1541, a search of pertinent historical narratives was made, in an effort to determine the appearance of Cerro Colorado crater prior to 1907. This produced the following lack of information:

1541—Journey of Melchior Diaz—no useful

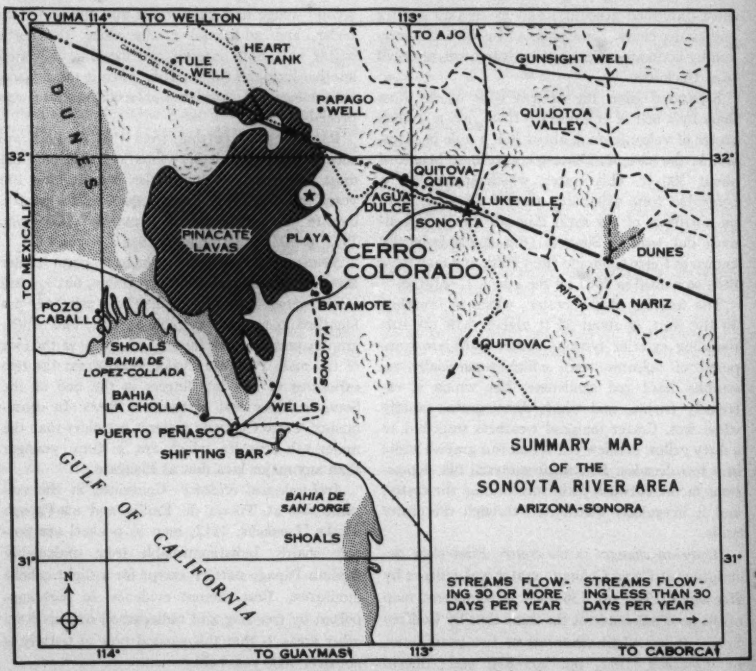

FIG. 2 – Map of the Sonoyta River area, showing location of Cerro Colorado crater in relation to the Pinacate lavas, and to local culture as of 1954

information [*Winship*, 1904, *Bolton*, 1949, pp. 169–176].

1698–1706—Narratives of Juan Mateo Manje, Eusebio Francisco Kino, Juan Maria Salvatierra, Manuel de la Oyela y Velarte, and others—many clear descriptions of the Pinacate Region and its landmarks, definite identification of Pinacate as an extinct volcano, no description of Cerro Colorado crater or anything resembling it [*Bolton*, 1948; *Ives*, 1942].

1745–1755—Diaries, narratives, and court records by and about Jacobo Sedelmayr, Juan Nentvig, Enrique Ruhen, Ignaz Pfefferkorn, Juanico of Sonoyta, and Luis Oacpicagigua—no specific descriptions of Cerro Colorado crater [*Dunne*, 1955; *Ewing*, 1945; *Guiteras*, 1894; *Ives*, 1939, in press; *Mills*, 1932, *Treutlein*, 1949].

1774–1776—Narratives and accounts of Juan Bautista de Anza, Francisco Garces, Juan Diaz, Pedro Font, and Tomas Eixarch—no useful information. Descriptions of the terrain not on the optimum route from Sonoyta to Yuma are extremely vague [*Bolton*, 1930, 1931].

1856–1857—Narratives and documents relative to the Crabb Filibustering Expedition into Sonora—no useful information [*Forbes*, 1952; *Villa*, 1951].

In none of these accounts is there any mention of an explosive eruption at Pinacate, either directly observed, or described by Indians.

Summary—Time of formation of Cerro Colorado crater can be placed between the years 1000 and 1800 AD with great confidence by use of physiographic, geologic, and archaeological evidence. It can be said with almost as great confidence that the ash beds at Pinacate, which are certainly not younger than Cerro Colorado, were deposited prior to 1650. After that date, any extensive ashfall would have been recorded at one or more of the Jesuit missions of Sonora, and prevailing winds are such that a large ashfall could not have occurred unobserved.

Lack of mention of Cerro Colorado crater in the accounts of Kino and his companions is interesting, but is not convincing evidence that the crater was not there in 1698.

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The Interpretation of Lead-Age Discrepancies by Acid-Washing Experiments

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Abstract—Powdered samples for which isotopically controlled age determinations were available have been subjected to mild acid washes. Correlations were obtained between the age patterns of the samples and the isotopic composition of lead in the bulk samples and the acid washes. The bearing of these data on the problem of U/Pb, Pb/Pb and Th/Pb age discrepancies is discussed. The amount of loss of various lead isotopes from a mineral is not necessarily proportional to their abundances in a given sample at present.

Introduction—The literature now records a substantial number of age measurements by the uranium-lead and thorium-lead methods which include isotopic analyses of lead. A sufficient number of determinations have been made to demonstrate that discrepancies frequently occur among the various ages calculated for a single sample which lie far outside of the expected analytical errors. These discrepancies are often found in spite of the most careful selection of samples. The calculated isotopic ages for a given mineral are based on the following assumptions: (1) The analytical data are correct within experimental errors. (2) The mineral contained no lead at the time of formation or else the initial lead content can be measured and corrected for by the use of Pb^{204} as an index. (3) The mineral assumed a given amount of uranium, thorium, or both at the time of formation and the concentrations of these elements were not changed subsequently by any processes other than radioactive decay. (4) The radiogenic lead found in the mineral today is an accurate measure of the amount of uranium or thorium decay or both which has taken place since the time of formation; that is, lead has not been lost from the mineral or added to it from outside sources. (5) There has been no loss at any time of intermediate daughter products such as radon, ionium or radium during the decay of uranium and thorium to their respective lead end products.

If all of these conditions are satisfied, the three independent isotopic ages which are determined by the ratios U^{238}/Pb^{206}, U^{235}/Pb^{207}, and Th^{232}/Pb^{208} will agree within the limits of analytical errors. When any two of the isotopic ages fail to agree it is obvious that at least one of the assumptions has been violated. Although violations of assumptions (1) and (2) may be responsible for some of the discrepancies which have been found [with regard to assumption (2), see *Stieff, Stern*, and *Milkey*, 1953] the present paper will deal with possible failures of assumptions (3), (4), and (5) which the author believes are responsible for most of the age discrepancies which have been reported. Failure of any of these three assumptions means in a general sense that there have been separations of the parents, uranium and thorium, from their stable lead daughters or intermediate decay products by processes other than those due to radioactive decay. In other words there has been a transport of materials in or out of the crystals. If such transfers of materials have indeed occurred in samples which exhibit discordant isotopic ages we may ask whether any detectable indications of the transfers remain within the samples today, whether materials entered or left the crystals and whether the parents, lead daughters, or intermediate decay products or all are involved in these transfers.

The purpose of this paper is to give the results of some acid-washing experiments which apparently contain information on these questions. The experiments were conducted as follows: Powdered samples, usually ground to pass 40-mesh, which had previously been used for age-determination work were washed for 15 minutes in cold 6 M hydrochloric acid. The isotopic composition of the lead so removed was compared with that from the original sample and in some cases the uranium and thorium contents of the acid washes were also determined. In general the acid washes removed from one to two per cent of the lead from a sample. The Tory Hill zircon was boiled 15 minutes in 1:1 aqua regia to obtain the soluble lead reported for this mineral. These experiments are semi-quantitative in nature since no work has been done to determine the effects of varying the washing conditions or the grain size of the samples. The results are thus significant insofar as they disclose trends but are probably not of rigorous quantitative significance in regard to the data on the acid soluble phases of the samples. However, a number of

valuable conclusions can be drawn from the data in its present form.

Results—The results of the experiments are given in Tables 1 and 2. The uranium and thorium contents of the minerals are believed to be accurate to about ±1 per cent, the Pb^{206} concentrations to about ±2 to 2½ per cent. The ages are accurate in most cases to about ±3 to 5 per cent with regard to analytical errors. The lead ratios are given in terms of Pb^{204} since this method of presentation seems necessary for clarity. It should be realized that the Pb^{204} abundance is the least accurately known of all the isotopic abundances for the leads. In general the relative abundances of Pb^{206}, Pb^{207}, and Pb^{208} could be determined to ±1 to 1½ per cent while the relative abundance of Pb^{204} could be determined to ±1½ to 5 per cent, the accuracy decreasing with decreasing abundance. An asterisk after a given lead isotope, for example Pb^{*208}, refers to a radiogenic lead from which the primary lead has already been subtracted. The primary leads were obtained directly from the isotopic composition of the lead in potassium feldspars at Tory Hill and Quartz Creek. For the remaining samples the primary lead corrections were inferred from the galena ore curves of *Collins*, *Russell*, and *Farquhar* [1953]. For a billion-year-old mineral the common lead correction is approximately 206/204 = 16.8, 207/204 = 15.5, and 208/204 = 36.4. The analytical data are treated in more detail in the original papers.

Because of the way in which this work evolved, the age data for Tory Hill sphene and Uncompahgre biotite-xenotime are given for the acid washed samples in Table 2. In all remaining cases the age data are for the unwashed samples. Two separate sphene samples were studied at Tory Hill.

TABLE 1 – *Percentages of U, Th, and Pb in bulk samples which entered acid washes*

Sample	Per cent soluble		
	U	Th	Pb
Sphene II, Tory Hill, Ontario	20	59	66
Zircon, Tory Hill, Ontario	...	...	15[a]
Biotite-xenotime, Uncompahgre, Colo.	2.7	1.6	...
Monazite, Houtenbek, S. Africa	7.3	1.8	4.8
Monazite, Quartz Creek, Colo.	5.2	2.8	1.7
Monazite, Goodhouse, S. Africa	2.0	1.7	1.4
Microlite, Quartz Creek, Colo.	...	...	2.0
Columbite-tantalite, Quartz Creek, Colo.	...	...	18

[a] Acid wash for this sample was hot 1:1 aqua regia. All other acid washes were cold 6 M hydrochloric acid.

Sphene I was a coarse sample for which the U^{238}/Pb^{206} age was determined on aliquots for a single dissolved sample. Sphene II was a finely ground sample prepared from a portion of sphene I. Since the lead data show that sphene II has a different concentration of radioelements from sphene I, separate entries are made in Table 2 for the two samples.

Sphene, Tory Hill, Ontario—These data are taken from the work already reported by *Tilton* and others [1955]. The thorium-lead age of the mineral is incompatibly low with respect to good uranium-lead ages from this district, which run about 1050 m y (million years). Patterson noted that a substantial amount of lead was removed when the mineral was washed with cold dilute hydrochloric acid and that the lead in the acid-soluble fraction contained a much larger percentage of the radiogenic Pb^{208} of the mineral than of the radiogenic Pb^{206}. Subsequent study showed that 59 pct of the thorium in the sample entered the acid washings while only 20 pct of the uranium from still another sample was soluble under the same conditions. Thus the low thorium-lead age for this mineral is accompanied by excesses of acid soluble thorium and radiogenic Pb^{208} compared to uranium and radiogenic Pb^{206}. A number of other examples of this general pattern follow.

Zircon, Tory Hill, Ontario—These age data are taken from the same source as the sphene just discussed. The sample has a low thorium-lead age and like the sphene from the same granite, has an excess of radiogenic Pb^{208} compared to radiogenic Pb^{206} in the acid washings. The uranium and thorium contents of the acid washings have not been studied.

Biotite-xenotime, Uncompahgre Granite, Colorado—The sample consisted of biotite with xenotime inclusions which probably account for most of the uranium and thorium in the sample. The U^{238}/Pb^{206} age of the mineral appears unreasonably high. More recent work of Aldrich, Davis and Wetherill at the Carnegie Institution indicates an age of around 1400 m y for this sample. Inspection of the acid-wash data shows that a marked excess of radiogenic Pb^{206} over radiogenic Pb^{208} entered the washings as well as an excess of uranium compared to thorium. This observation in itself tends to make the U^{238}/Pb^{206} age suspect.

Monazite, Houtenbek, South Africa—The analytical data for this monazite have been given by *Nicolaysen* [1954]. The age of the mineral is believed to be fixed by the agreement of the Pb^{207}/Pb^{206} and Th^{232}/Pb^{208} ages as about 930 m y. The

TABLE 2 — *Results of acid-wash experiments*

Sample and source	Content			Age in millions of years				Isotopic Composition*					Th/U
	Uranium	Thorium	Pb^{204}	U^{238}/Pb^{206}	U^{235}/Pb^{207}	Pb^{207}/Pb^{206}	Th^{232}/Pb^{208}	Pb^{204}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}	$\frac{Pb^{*207}}{Pb^{*206}}$	$\frac{Pb^{*208}}{Pb^{*206}}$	
	ppm	ppm	ppm										
Sphene I, Tory Hill, Ont.	303	...	68.4	910	...	...	...	39.13[b]	17.11[b]	79.38[b]	...	...	...
								...	...	...	...	...	...
Sphene II, Tory Hill, Ont.	...	2205	39.9	...	...	1090	450	108.6[b]	22.18[b]	146.2[b]	0.075[b]	1.2[b]	...
								21.78	15.73	69.30	...	4.8	...
Zircon, Tory Hill, Ont.	2650	2180	392	1030	1050	1090	390	8535	639	826	0.075	0.097	...
								132.4	24.24	117.6	0.077	0.706	...
Biotite-Xenotime, Uncompahgre, Colo.	15.65	194	9.97	3180	2065	1640	1100	111.7[b]	24.69[b]	143.5[b]	0.099[b]	1.13[b]	12.4[b]
								80.8	21.51	47.5	0.097	0.18	7.3
Monazite, Houtenbek, S. Africa	4480	110,000	945	1400	1230	930	940	924	78.3	4610	0.069	5.04	24.6
								7000	526	1530	0.073	0.22	6.0
Monazite, Quartz Creek, Colo.	1415	49,300	343	1590	1420	1170	995	1010	92.9	6660	0.078	6.67	34.8
								82.3	18.4	185	0.047	2.27	19.2
Monazite, Goodhouse, S. Africa	2146	83,300	293	930	915	880	900	530	50.2	6100	0.067	11.8	38.8
								189	26.7	1640	0.065	9.3	31.6
Microlite, Quartz Creek, Colo.	62,100	...	8150	915	1055	1350	...	1593	149.4	40.56	0.085	0.0031	...
								975	102.3	58.1	0.091	0.023	...
Columbite-Tantalite, Quartz Creek, Colo.	1281	...	337	1520	1470	1390	...	122.7	24.50	55.77	0.087	0.19	...
								85.6	22.4	57.3	0.10	0.31	...
Uraninite, Bob Ingersoll Mine, S. Dak.	645,500	29,300	152,800	1580	1600	1630	1440	33,590	3327	464	0.0986	0.0128	...
								9620	912	149	0.0934	0.0118	...

* Radiogenic leads from which primary lead has been subtracted.

[a] Upper value is for total sample, except as noted by [b]; lower value is for acid-soluble portion.

[b] Acid-washed sample.

reasons for believing this are that thorium-lead ages clearly tend to be too low when they are in error while the high U^{238}/Pb^{206} age indicates the Pb^{207}/Pb^{206} would tend to be too high if it were in error. Since the two ages agree they probably determine the true age of the mineral. It is realized that this interpretation could be in error and that more work is needed at this site to fix the age accurately. The high uranium-lead ages are accompanied by the entry of substantial excesses of radiogenic Pb^{206} and uranium relative to radiogenic Pb^{208} and thorium into the acid wash. For this sample the ages are brought into somewhat better agreement if one calculates them from the acid washed sample. The ages are then: U^{238}/Pb^{206}, 1180 m y; U^{235}/Pb^{207}, 1080 m y; Pb^{207}/Pb^{206}, 875 m y; and Th^{232}/Pb^{208}, 950 m y. The ages of the Quartz Creek monazite, which is discussed next, are not improved when they are calculated from the acid washed rather than the unwashed sample. The Houtenbek monazite is the only case among all the examples cited here for which the acid soluble lead is more radiogenic than the lead in the total sample.

Monazite, Quartz Creek, Colorado—The age of the Brown Derby pegmatite from which this sample was taken is believed to be 1375 ± 100 m y, on the basis of Rb/Sr, K/A, and other uranium-lead work done on various minerals from the pegmatite. The data for this conclusion will appear in a separate publication [*Aldrich* and others, in preparation]. The U^{238}/Pb^{206} age is too high and the acid washings from the sample contain excesses of radiogenic Pb^{206} and uranium compared to radiogenic Pb^{208} and thorium in the sample. It should be noted that the thorium-lead age for this mineral is apparently too low, but that the high solubility of uranium and Pb^{206} has masked any effects which might have resulted from the low thorium age. The percentage of thorium entering the acid wash from this monazite is about twice as large as that for the Houtenbek and Goodhouse monazites which apparently have good thorium-lead ages, but it is not possible to say at this time how much significance can be attached to this observation. The ages calculated for this monazite from the acid washed sample are: U^{238}/Pb^{206}, 1620 m y; U^{235}/Pb^{207}, 1420 m y; Pb^{207}/Pb^{206}, 1185 m y; and Th^{232}/Pb^{208}, 1015 m y. These ages represent no improvement over the ages calculated for the unwashed sample. Of particular interest for this sample is the extreme contrast between the radiogenic Pb^{207}/radiogenic Pb^{206} ratio of the lead in the sample and the acid wash. The lead in the acid wash has a Pb^{207}/Pb^{206} ratio which would be associated with a 'young' mineral with an age of approximately 100 m y, although it is difficult to ascertain a Pb^{207}/Pb^{206} age for the lead in the acid soluble phase.

Monazite, Goodhouse, South Africa—For the analytical data see *Nicolaysen* [1954]. This monazite gives good agreement of ages at about 900 m y. In this case uranium and thorium enter the acid wash in about equal percentages. The isotopic composition of the acid soluble lead is quite similar to that of the total sample except for the presence of a relatively higher proportion of common lead in the acid soluble fraction.

Microlite, Quartz Creek, Colorado—Analytical results for this mineral are in the process of publication [*Aldrich* and others, in preparation]. This sample is also from the Brown Derby pegmatite. The type of age pattern given by this mineral is one which is commonly encountered in lead-age work. There is no significant feature of the acid wash data in Table 2 which one might correlate with the age pattern. It was initially hoped that some relation might exist between the age pattern and the Pb^{*207}/Pb^{*206} of the acid soluble lead and that in the total sample. Actually no correlations between the age pattern and the acid soluble Pb^{*207}/Pb^{*206} ratios have been found in the work to date. More work in the future may ultimately reveal some sort of relationship.

Columbite-tantalite, Quartz Creek, Colorado—This mineral came from the same hand specimen which contained the monazite mentioned earlier. The columbite-tantalite and monazite occurred together in a matrix of albite and quartz, the albite having an abundance of about 85 pct. The acid soluble lead is of little help in interpreting the age pattern of this mineral. However it will be useful in later discussion to compare the acid soluble lead in the columbite-tantalite with that of the neighboring monazite. It is also interesting to note in Table 1 that the columbite-tantalite, like the sphene from Tory Hill, possesses a high percentage of acid soluble lead.

Uraninite, Bob Ingersoll Mine, South Dakota—For the detailed analytical data see *Wetherill* and others [in press]. The thorium-lead age for this sample is about ten per cent low. An attempt was made to look for a possible reflection of this fact in the isotopic composition of the lead in the acid wash but none was found. This may be due in part to sampling errors since the age analyses were made on a single crystal which was completely

dissolved, making it necessary to select a second crystal for the acid wash experiment.

Discussion—In the data obtained thus far there are striking correlations between the age patterns of minerals and the results of the acid washing experiments. Two minerals with low thorium-lead ages have acid soluble leads which contain substantial excesses of radiogenic Pb^{208} over radiogenic Pb^{206} relative to the amounts of these isotopes in the total samples. Several minerals with high uranium-lead ages have acid soluble leads which contain excesses of radiogenic Pb^{206} over radiogenic Pb^{208}. Moreover, in those cases where the acid washes have been analyzed for uranium and thorium, excesses of soluble radiogenic Pb^{208} are accompanied by excesses of soluble thorium relative to uranium and excesses of soluble radiogenic Pb^{206} are accompanied by excesses of soluble uranium relative to thorium. Examples are the low thorium-lead age for the Tory Hill sphene and the high uranium-lead ages for the Uncompahgre biotite-xenotime, the Houtenbek monazite and the Quartz Creek monazite. These observations indicate that the transfers of material, which are the cause of lead age discrepancies, involve both parent and daughter elements. For example, a low thorium-lead age does not result from a removal of Pb^{208} from a crystal while all the thorium remains in the lattice, but rather both thorium and Pb^{208} have been removed from the crystal with the loss of Pb^{208} being the greater. The Goodhouse monazite has apparently suffered little transport of uranium, thorium and lead as evidenced by the good agreement of the various lead ages for this mineral. The analyses of the acid soluble fractions of this mineral indicate that the distribution of uranium, thorium and their respective daughter leads within the sample is relatively 'homogeneous.' More observations are necessary in order to tell whether this will prove to be the general case. It seems entirely possible that a mineral might exhibit agreement between the isotopic composition of lead in the bulk sample and acid washings and still possess a discordant age pattern.

The problem of the cause of age discrepancies—Although the literature commonly states that low uranium-lead ages accompanied by higher lead/lead ages give evidence for losses of lead by such samples, it can be shown from the mathematics of the age equations which have been generalized to include losses or gains of parent and daughter that it is impossible to distinguish gain of uranium from loss of lead (with the same radiogenic Pb^{207}/radiogenic Pb^{206} as that of the total sample) at any given time. Also a simultaneous loss of parent and daughter with the loss of daughter predominating will produce an effect on the age pattern which will be indistinguishable from that due solely to the loss of an amount of daughter which is equal to the excess over the amount of parent lost. We must appeal to criteria other than the age patterns of minerals to establish whether lead loss is the cause of low ages. With the aid of the acid wash data on the minerals of this study we may investigate whether gain or loss of materials is the more likely cause of age discrepancies. It is reasonable to assume that the acid soluble materials characterize, at least qualitatively, the immediate environment of the crystals. That is, they represent the materials immediately adjacent to the grain boundaries and the materials which fill the cracks and fissures present in the crystals. We now inquire whether the materials in this environment have originated from the crystals themselves or from some external source. In all the cases given in Table 2 there are general similarities between the composition of the acid soluble materials associated with the minerals and the minerals themselves which suggest that the soluble materials derive from the minerals rather than from an external source. The acid soluble fractions of the monazites all contain high Th/U ratios which are characteristic of monazites and, with the exception of the Houtenbek sample, high ratios of Pb^{208} to Pb^{206} in the acid soluble leads which are again characteristic of monazites. A particularly convincing comparison is found in the data for the monazite and columbite-tantalite at Quartz Creek. It will be recalled that these two minerals occurred together in a matrix of albite and quartz. Inspection of Table 2 shows that the soluble lead in the monazite has a Pb^{*208}/Pb^{*206} of 2.3 while that in the columbite-tantalite has a Pb^{*208}/Pb^{*206} of 0.3. That is, the relative amounts of radiogenic Pb^{206} and Pb^{208} in the acid soluble fractions of the minerals follow those in their respective host minerals. If the acid-soluble leads in these two minerals were originating from an external source we would expect them to have relatively similar isotopic compositions. It appears then that the acid soluble fractions represent loosely bound materials which are derived from the host minerals. The data now at hand suggest that incorrect uranium-lead and thorium-lead ages result from the loss of both parent and daughter from a mineral and that the measured ages will be too high or too low according to whether the loss of parent or daughter has predominated.

All the foregoing discussion has dealt with the loss of the parents, uranium and thorium, or the stable lead isotopes which are the end products of their decay. It was mentioned earlier that loss of intermediate daughter products in the decay chains might also cause age discrepancies. In considering this point it is well to remember that the U^{238} decay chain possesses a Th^{230} daughter with a mean life of 115,000 years and a Ra^{226} daughter with a mean life of 2300 years. The U^{235} chain has a Pa^{231} daughter with a mean life of 49,000 years. These periods of time may well be sufficient to allow chemical fractionations to take place. The longest-lived member of the thorium decay chain is Ra^{228} with a mean life of 9.7 years.

Kuroda [1955] has presented evidence in his work on the isotopic composition of radium in uranium ores that fractionations of intermediate daughters do in fact occur in the uranium decay chains. He found that the activity ratio of Ra^{223} to Ra^{226} in 32 different samples from 28 localities varied from 0.046 (the value to be expected from the present-day activity ratio of U^{235} to U^{238}) to a value as high as 0.13 for a Utah carnotite. Ratios of around 0.05 were frequently encountered in pitchblendes and uraninites. The uraninite from Wilberforce, where good agreement between uranium-lead ages has been obtained (Nier, 1939), gave an activity ratio of 0.046. Samples where uranium-lead age discrepancies have been found; for example, Joachimsthal pitchblende, Great Bear pitchblende, Ruggles Mine uraninite, gave activity ratios which departed substantially from 0.046.

Kuroda's work would seem to add an interesting new dimension to the discussions of the present paper. The lack of uniformity in the leaching of radiogenic Pb^{208} with respect to radiogenic Pb^{206} for the samples reported in Table 2 could conceivably arise from an initial heterogeneous distribution of uranium with respect to thorium in the samples. That is, radiogenic Pb^{208} might have a greater tendency to leach than radiogenic Pb^{206} because thorium was initially distributed nearer to crystal boundaries than was uranium. In the case of Kuroda's work, however, U^{238} and U^{235} must have had similar distributions in the crystals. In spite of this, inhomogeneities have developed in the distribution of the radium isotopes of the two decay chains. Moreover, Kuroda's findings require that in the course of approximately the past 100,000 years, at most, materials from the U^{238} decay chain have been transported entirely out of the samples or, less likely, that materials from the U^{235} decay chain have been transported into the samples. We conclude, then, that even with an initially uniform distribution of uranium and thorium with respect to each other in a crystal, it is possible for processes to occur which will fractionate the daughter products of the decay chains and lead ultimately to a heterogeneous distribution of radiogenic Pb^{208} with respect to radiogenic Pb^{206}. Even the radioactive precursors of Pb^{206} and Pb^{207} may be fractionated by these processes.

Holmes [1955] has published an interesting example of a monazite from a pegmatite near Bangalore, Mysore, India which appears to have a low thorium-lead age and which gives no detectable radon leakage, but gives a thoron leakage of about one per cent as now measured in the laboratory. This is a demonstration of inhomogeneities which are in harmony with the findings of the present paper.

Although useful correlations with the age pattern have been obtained from comparisons of radiogenic Pb^{208} to radiogenic Pb^{206} ratios in minerals and their associated acid soluble phases, no significant correlations have been found in the radiogenic Pb^{207} to radiogenic Pb^{206} comparisons. The Pb^{*207}/Pb^{*206} of the acid soluble lead is somewhat higher than that of the total sample for the Houtenbek monazite, Quartz Creek microlite and columbite-tantalite, is essentially the same in the acid soluble phase and total sample for the Tory Hill zircon, Uncompahgre biotite-xenotime, and Goodhouse monazite, and is somewhat lower for the acid soluble lead for the Ingersoll uraninite and decidedly lower for the acid soluble lead of the Quartz Creek monazite. No correlation seems to exist between these comparisons and the age patterns exhibited by the minerals.

With the exception of the Houtenbek monazite, the acid-soluble leads all contain a larger fraction of common lead compared to radiogenic lead than do the total mineral samples. This additional common lead could arise either from handling in the laboratory or from natural sources in the field. The Tory Hill and Uncompahgre minerals were separated from granites and could have been contaminated in the separation process. However the handling which the remaining mineral samples received involved only the crushing of large single crystals in a diamond mortar and thus gave less chance for contamination. The fact that the soluble lead of the Houtenbek monazite was more radiogenic than that of the total sample in spite of the crushing operation makes it seem probable that the additional primary lead in the samples is of

natural origin. It may arise from deposits left by ground waters, for example.

Conclusions—The transfers of materials which give rise to discordant uranium-lead and thorium-lead ages have in many cases left recognizable indications which can be detected in the laboratory today. Evidence has been given for believing that both the parent and daughter elements are lost from a mineral in such cases and that the ages will be too low or too high according to whether the loss of parent or daughter has predominated. Some of the loss of lead may be due to a loss of intermediate daughters in the decay chains rather than to a loss of lead itself. The loss of lead isotopes occurring at the present day from a given sample is not necessarily in proportion to their abundances in the total sample. This is especially true of Pb^{208} and Pb^{206} and is true in several cases even for Pb^{206} and Pb^{207}.

Finally it should be emphasized that the present investigations have made no attempt to localize the sources of the acid soluble materials in the samples. The samples were generally believed to be of 99 pct purity or greater. Possible exceptions might be the Tory Hill sphene and the Uncompahgre biotite (which may have contained other minerals in addition to the xenotime which was observed). Part or all of the acid solubility phenomena attributed to the minerals may be due to small inclusions of uraninite, thorite, allanite, etc. Thin sections of individual monazite crystals from the Quartz Creek pegmatite show extensive filling of the cracks with an orange-brown material of unknown composition. Thin sections of the Goodhouse monazite fail to show the presence of such material in the cracks. However, the fact remains that the samples as analyzed gave age discrepancies which were related to the acid wash data regardless of whether these observations originated from the minerals or from their trace impurities. It is quite certain that the mineral samples compare favorably in purity with those which have been used in other age determination studies. Careful control of the purity will be desirable in future work directed towards an improved understanding of the acid solubility phenomena.

Acknowledgments—The results for the Tory Hill and Uncompahgre samples were obtained during collaborative work with C. C. Patterson of the California Institute of Technology. The data for the South African monazites were part of a collaborative study with L. O. Nicolaysen, then a graduate student in the Department of Geology at Princeton University. Discussions with these and other colleagues, notably L. T. Aldrich, G. L. Davis, and G. W. Wetherill of the Carnegie Institution of Washington have been helpful in formulating the present discussions.

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Trigonometric Solution from Apparent Dip

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Abstract—The apparent-dip problem may be solved easily, quickly, and accurately by elementary trigonometry.

The apparent-dip problem consists essentially of two cases: (1) the case in which the true strike and an apparent dip are given, and (2) the case in which two apparent dips and the angle between them are given.

Several solutions have been developed. The stereo net may be used to solve either case. Construction (laying off the contangents of the apparent dips) may be used to solve either. A formula for solving Case 1 is well known; *Tanner* [1953] has outlined a procedure for actually using apparent dip in the course of making field measurements. *Gabriel* and *Pierson* [1953] have applied

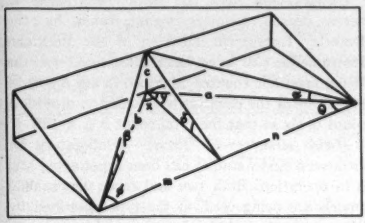

FIG. 1 - Elements of the apparent-dip problem

a form of vector analysis to Case 2, justifying the more complex procedure by the greater accuracy obtained.

Case No. 2 may be solved by elementary trigonometry to any degree of accuracy desired within the limits of the trigonometric tables available, and without forcing the student to learn any new mathematical notation. The procedure requires substitution of known values in the three numbered formulas developed below.

In Figure 1, set $c = 1$. Then $\cot \alpha = a$ and $\cot \beta = b$. Now by the law of cosines

$$\cos \phi = \frac{b^2 + (m+n)^2 - a^2}{2b(m+n)} \tag{1}$$

$$(m+n)^2 = b^2 + a^2 - 2ab \cos (x+y) \tag{2}$$

and by the law of sines

$$m + n = \frac{a \sin (x+y)}{\sin \phi} \tag{3}$$

Substituting (2) and (3) into (1) gives

$$\cos \phi = \frac{b - a \cos (x+y)}{a \sin (x+y)} \sin \phi$$

or

$$\cot \phi = \frac{b - a \cos (x+y)}{a \sin (x+y)}$$

or

$$\cot \phi = \frac{\cot \beta - \cot \alpha \cos (x+y)}{\cot \alpha \sin (x+y)} \tag{4}$$

Also

$$x = 90 - \phi \tag{5}$$

and

$$\cot \delta = \cot \beta \sin \phi \tag{6}$$

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Station Development

New equipment—Automatic-calibration weight lifters for daily checking of amplitude response and phase have been attached to Benioff reluctance instruments at Pasadena, Tinemaha, and Isabella. Red safe lights of an improved type have been installed at most of the stations; these allow the use of a lighter and less expensive grade of recording paper. The vertical-component recorder at Dalton has been transferred from film to the new paper.

Three small house trailers are being outfitted as portable stations. Two portable seismographs using vertical and horizontal pendulums and variable discriminator transducers have been set up to record by the hot-stylus method, and are maintained in reserve for emergencies. Several additional film-recording units can be put into the field on short notice.

New instruments—Lehner has designed and installed at Pasadena a horizontal-component accelerograph with $T_0 = 0.11$ sec and $V = 600\pm$. Strong-motion torsion instruments ($T_0 = 0.8$ sec) recording on film, with effective magnifications of 100 and 4, have been added at Haiwee, Isabella, and Riverside. A standard torsion instrument ($T_0 = 0.8$, $V = 2800$) has been added at Isabella. Long-period Benioff reluctance instruments ($T_0 = 1$ sec, $T_g = 90$ sec) are now recording in all three components at Pasadena, Riverside, Barrett, and Tinemaha.

Instrument Development

Vertical component seismograph (H. Benioff)—A vertical component seismograph having a pendulum period of 13 sec has been operated since March 31, 1955. The pendulum employs an elinvar-type alloy spring in a modified Lacoste configuration. The inertia reactor is in the form of a rectangular bar arranged with the axis of rotation at one end. The spring is attached at the midpoint. A transistor-operated carrier current variable discriminator transducer provides power for recording with a four-second period galvanometer. For wave periods longer than 13 sec the seismograph has a frequency response approximately equivalent to a Milne-Shaw seismograph.

Tubeless photocell-galvanometer amplifier (H. Benioff)—An amplifier consisting of a galvanometer and two cadmium sulfide photo-conductive cells in a push-pull circuit without vacuum tubes has been developed. This device provides output currents proportional to the galvanometer deflection and of sufficient magnitude to operate direct writing recorders of the Esterline-Angus ink and Sanborn heated stylus types, or a magnetic tape recorder. The power gain is of the order of 10^9. Stability is excellent owing to the use of negative feedback.

Quartz-crystal clock (H. Benioff)—A series of seven decade counters manufactured by the Berkeley Instrument Division of the Beckman Instruments Co. have been substituted for the Wang magnetic counter described in our report of 1953. One of the counters is modified to provide a count of six so that the total count is 6×10^6.

Model seismology (F. Press)—A laboratory for ultrasonic model studies has been constructed and is in operation. Both two and three dimensional models are being used, of the type described by *Oliver*, and others [1954]. Instrumental innovations have been incorporated, making possible better control of initial pulse width and shape and improved signal to noise ratio. The Rayleigh wave method of exploration, described below, is now being modeled.

Long-Period G Waves (H. Benioff)

It is suggested that the absence of significant dispersion in G waves mentioned in our previous report is related to the duration of faulting at the source. In order to generate a non-dispersive wave, the duration must be sufficiently long to concentrate most of the wave energy into components within the period range above 25 sec corresponding roughly to the short period limit of the approximately constant segment of the dispersion curve.

Local Phase Velocity (F. Press)

Rayleigh waves which have traversed long oceanic paths have been used to determine crustal structure in Southern California. Comparing observed phase velocities with an experimentally

determined phase-velocity curve representative of the average continental crust we have found normal crustal thickness (35 km) in the Peninsular range province, a 50 pct increase in thickness under the southern Sierra Nevada, and a decrease in thickness by as much as 50 pct in the offshore continental borderland.

Crustal Structure from Gravity Data (C. Tsuboi)

Chuji Tsuboi, Visiting Professor from the University of Tokyo, has made several calculations on gravity data obtained in California. The results clearly indicate the thinning of the Earth's crust toward the Pacific and the thickening inland. His calculations also show that the density of the sediments in the Central Valley increases rather rapidly with depth, so that at depths more than 3000 ft the density does not differ much from that of rocks forming the crystalline basement. These results are in general agreement with those from the phase-velocity method.

Lg Waves in California (F. Press)

Velocity of Lg waves in the Sierra Nevada block is being investigated to establish whether elastic parameters of crustal rocks in orogenic belts are the same as in normal sections of the continental crust. Preliminary results for eleven paths indicate no significant difference.

Project Sponsored by the Geophysics Research Division of the Air Force Cambridge Research Center

Observations with the instruments described in our previous report have furnished records of 'storms' of regular microseisms with periods of four to nine seconds which have been studied by Gutenberg. In most instances there was no definite correlation with low-pressure areas; correlation with high ocean waves, which previously has been found to be good, has not yet been investigated in these cases. In nearly all instances the microseismic waves came from the south-west quadrant. Their velocity was 3.1 ± 0.2 km/sec. Calculations by Press on the basis of earthquake Rayleigh wave velocities yield 3.2 km/sec for periods of seven seconds. In the majority of about 100 instances the combined study of records of the tripartite vertical instruments, two horizontal-pendulum seismographs and two horizontal-strain seismographs, as well as a number of combined output configura-

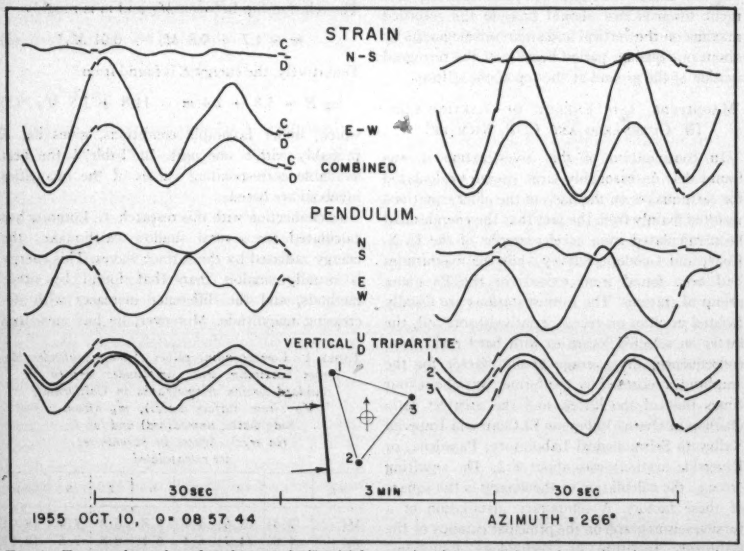

Fig. 1 – Two portions of earthquake records (Rayleigh waves) written at Palomar by various instruments built under the project sponsored by the Geophysics Research Division of the Air Force Cambridge Research Center

tions, indicates that the waves fulfill all requirements of Rayleigh waves. Occasionally, waves show clear indication of surface shear characteristics and sometimes confused motion indicates superposition of waves of the two types. Since the tripartite instruments record the vertical component, the velocity of surface shear waves can not be found at the Palomar installation.

Repeatedly, portions of earthquakes were recorded during the approximate five minutes when the various instruments were operating during each hour (speed 3 mm/sec). Most of the recorded surface waves have the characteristic properties of Rayleigh waves. Figure 1 shows portions of such waves produced by an earthquake of magnitude 7½± originating about 08h 57m 44s GCT on October 10, 1955, near 5°S, 153°E (New Britain). The waves should have arrived from a direction a few degrees south of west. In excellent agreement with the records, Rayleigh waves should produce a much larger displacement on the EW component pendulum than on the NS, a much larger compression on the EW than on the NS component of the strain seismograph which, on the record, should be nearly in phase with the recorded relatively large vertical displacement; considering the properties of our instruments, the recorded maximum displacement towards east should precede the recorded maxima on the vertical and strain seismographs by about one quarter period because of the retrograd motion of the ground at the top of the ellipse.

Magnitude and Energy of Earthquakes (B. Gutenberg and C. F. Richter)

In continuation of this investigation it was found that unreasonably large energies calculated for earthquakes on the basis of the older equations resulted mainly from the fact that the energies had been calculated from accelerographs of the U. S. Coast and Geodetic Survey while the magnitudes had been found from records of the Pasadena group of stations. The former stations are usually located in cities on recent, relatively soft soil, the latter on selected localities with hard rock. As a consequence, the average ground factor for the amplitudes recorded by the former was about four times that of the latter, and the greatest ratio (Bishop in Owens Valley or El Centro in Imperial Valley to Seismological Laboratory, Pasadena, or Riverside station) was about 8:1. The resulting error in the calculation of the energy is the square of these factors. A temporary installation of a torsion seismograph on the principal campus of the California Institute of Technology (alluvium) furnished records of near-by earthquakes with amplitudes about four times those recorded by a similar instrument at the Laboratory (on granitic rock) about three miles away. Before and after the experiment the two instruments furnished almost identical seismograms side by side at the Laboratory. During the experiment surface waves of teleseisms were also practically identical.

Another source of error resulted from the fact that three imperfectly consistent magnitude scales had been in use: M_L determined from records of local earthquakes in California according to the original definition by Richter; M_S from the amplitudes of surface waves for shallow teleseisms; M_B found from the amplitude/period ratio of body waves for shallow and deep-focus teleseisms, including a correction for large shocks. It is now believed that the uncorrected magnitude m_B found from body waves offers the best basis for further research, and that approximately

$$m_B = M_S - 0.37\,(M_S - 6.76) \qquad (1)$$

Values of m_B calculated directly from body wave data by use of revised tables or graphs, and from surface wave amplitudes using (1) or a corresponding nomogram by Nordquist, are adjusted to a weighted mean, when both are available; this is termed the 'unified magnitude' and denoted by m. The relationship between M_L and m is roughly

$$m = 1.7 + 0.8\,M_L - 0.01\,M_L^2 \qquad (2)$$

Tentatively, the energy E is found from

$$\log E = 5.8 + 2.4\,m = 11.8 + 1.5\,M_S \qquad (3)$$

which, under favorable conditions, gives log E probably within one unit. In Table 1 the best available corresponding values of the quantities involved are listed.

In connection with this research, C. Lomnitz has calculated for several shallow earthquakes the energy radiated by the surface waves. This energy is usually smaller than that found by other methods, and the difference increases with decreasing magnitude. Moreover, he has measured

Table 1 – *Corresponding values of the magnitudes M_L (from maximum trace amplitudes written by standard torsion seismographs in California), M_S (from surface waves), m_B (from body waves, unmodified) and log E (in ergs); figures in parentheses are extrapolated*

M_L	3	4	5	6	7	8	(9)
M_S	(2.4)	(3.6)	4.7	5.8	6.8	7.9	(8.9)
m_B	(4.0)	(4.7)	5.4	6.1	6.8	7.5	(8.1)
log E	15.4	17.2	18.9	20.5	22.1	23.7	(25.2)

TABLE 2 – *Numbers of shocks having unified magnitudes m between 6 and 7*

m	Shallow shocks					Intermediate shocks					Deep shocks				
	6¼	6½	6¾	6	Total	6¼	6½	6¾	6	Total	6¼	6½	6¾	6	Total
1935	12	29	43	59	143	2	6	9	13	30	0	2	5	5	12
1936	16	25	40	63	144	6	5	6	14	31	1	5	3	3	12
1937	8	20	44	64	136	5	11	8	10	34	0	2	2	4	8
1938	9	18	36	59	122	5	17	3	16	41	1	2	3	3	9

the duration of the *P*-group in seismograms of shocks originating at different focal depths without finding any systematic differences for a given magnitude within the rather large limits of error.

The most complete International Seismological Summaries published thus far are probably those for the years 1935–1938. For these years the numbers of shocks having unified magnitudes m between 6 and 7 have been determined, those for 1935–1937 by Gutenberg, those for 1938 by C. Lomnitz. Table 2 contains the results in steps of $m/4$.

For the region of Woody, California, C. Lomnitz has confirmed the earlier finding by Richter and Nordquist for the Riverside, California, region that the increase in the number of earthquakes with decreasing magnitude continues to the smallest observable shocks recording barely above the unrest of the ground ($M_L = \frac{1}{2}\pm$, $m = 2\pm$). For five days during 1954 he found (in steps of $\frac{1}{2}M_L$)

M_L	2½	2	1½	1
number	3	2	7	16

ENERGY OF EARTHQUAKES (B. GUTENBERG)

The energy of all earthquakes with a unified magnitude of 6.9 or over which are listed in 'Seismicity of the Earth' has been recalculated by use of the unified magnitude m and (3). The average resulting energy released annually is about 10^{25} ergs (about 7.3×10^{24} in shallow, 1.6×10^{24} in intermediate, and 0.3×10^{24} in deep shocks). Since the heat escaping the Earth annually corresponds to almost 10^{28} ergs, and the heat generated inside the Earth is probably of the same order of magnitude, it is not unreasonable to assume that the earthquake energy results ultimately from heat liberated in radioactive processes. In an average year, more energy is released in the twenty largest shocks than in all smaller ones. About ⅔ of all earthquake energy is released in the upper 35 km of the crust and only about three per cent below 300 km. The energy release in the circum-Pacific and Alpide belts has a minimum near 300 km depth and a secondary maximum between 550 and 650 km depth. The maximum energy found for a single shock since 1904 decreases from about 10^{25} ergs in the upper 150 km of the Earth to slightly less than 10^{24} at a depth of 650 km. Below this depth it decreases rapidly to 10^{22} ergs at a depth of 700 km. This rapid decrease could be caused by a decrease of the apparent coefficient of viscosity from 10^{22} or 10^{22} poises in the crustal layers to about 10^{20} poises below 700 km, where flow processes would remove strain at least as fast as tectonic processes are building it up.

In the earliest years for which reliable data for energy release exist, starting with 1904, the energy release was relatively high in all depth ranges; it has been relatively low in most years since about 1939. The smallest energy release in shallow shocks in any calendar year, about 0.9×10^{24} ergs, was found for 1954; the corresponding smallest release in all shocks, about 1.2×10^{24} ergs, for 1930. The corresponding greatest releases are $3\frac{1}{2} \times 10^{25}$ ergs in shallow shocks and $4\frac{1}{2} \times 10^{25}$ ergs in all shocks during 1906, 10^{25} ergs in intermediate shocks during 1911, and ¾ $\times 10^{25}$ ergs in deep shocks during 1906.

An attempt is being made to collect information for years preceding 1904. During 1903, the energy release was apparently above average in all three major depth ranges. A large deep shock on January 4 in the Tonga sector had a magnitude of about $m = 7\frac{3}{4}$. Large shocks at intermediate depth include one on August 11 in the eastern Mediterranean ($m = 7\frac{1}{2}\pm$), and possibly shocks on June 2 off Alaska and on May 13 in the southern Pacific. Shallow shocks with $m = 7\frac{1}{2}$ to $7\frac{3}{4}\pm$ include shocks on January 14 (off Mexico-Guatemala), February 1 (SW of Lake Baikal), and on May 13 (S. Pacific, possibly deeper than normal). Other noteworthy shocks during 1903 include one intermediate Hindu Kush shock, on October 19 ($m = 7$ to $7\frac{1}{4}$), one shallow shock in the Indian Ocean near 34°S, 52°E with $m = 7\pm$, and a shock on February 10, $m = 7\frac{1}{2}\pm$?, felt at Guam, depth probably roughly 60 km.

UNIDIRECTIONAL FAULTING

Richter has restudied the literature bearing on the direction of progression of faulting in large

earthquakes, for correlation with findings in Southern California. In the majority of occurrences where observations are adequate, the evidence is that rupture begins at or near one end of the active fault segment. In a few instances, notably the California earthquake of 1906, rupture may have begun near the center; this is definitely the exception and not the rule. The widespread belief to the contrary is partly due to confusion between the epicenter determined from instrumental records and that inferred from the form of the isoseismals. Frequently the instrumentally determined epicenter is located very eccentrically with respect to the most heavily shaken area. Foreshocks usually occur near the point of initial rupture in the main shock; aftershocks scatter along the whole active fault segment, but tend to concentrate near the two ends.

Desert Hot Springs Earthquake (C. F. Richter and C. R. Allen)

Seismic and field studies of the Desert Hot Springs earthquake of December 4, 1948, are nearly complete. The main shock, of magnitude 6½, is placed at 33°56.4′N, 116°23.1′W. It was followed by several hundred aftershocks, 84 of which exceeded magnitude 3.0; these lasted into 1953. Energy released during the main shock far exceeded that of the aftershocks.

These earthquakes probably originated on the Mission Creek fault, a major branch of the San Andreas system. The epicenters are concentrated on a line about 18 km long, parallel to but five km north of the trace of the fault. This suggests a northerly dip of the fault plane of about 73°, which is consistent with exposures of the fault plane observed a few miles west of Desert Hot Springs. The strain release during the aftershocks is concentrated toward the two ends of the line of epicenters, which is a pattern similar to that of the Kern County earthquakes. The epicenter of the main shock is near the southeast end of the line of epicenters.

Early arrival times and anomalous $S - P$ intervals for some of the shocks at very near-by stations remain unexplained, as do abnormal delays at Palomar for many of the shocks.

Anelastic Properties of Rocks (C. Lomnitz)

Experimental results—Torsion creep experiments on slender rods of California granodiorite and gabbro have been summarized by the following stress-strain-time relation

$$\epsilon(t) = \frac{\sigma_0}{\mu}[1 + q \ln(1 + 2\pi a t)] \qquad (4)$$

where μ is the rigidity modulus and σ_0 is a constant shear stress not exceeding $5 \times 10^{-4}\,\mu$.

The experimental work was done at room temperature and atmospheric pressure. A torsion apparatus designed by Benioff is used, featuring continuous photographic recording at an amplification of 1 mm to 2.5×10^{-6} radian of twist per unit length. The average duration of each test was 10,000 min. Further work is in progress.

Theoretical results—Boltzmann's theory of dissipation in solids has been further developed to connect static and dynamic properties of solids. The case of constant internal friction over a wide range of frequencies is shown to correspond to a creep equation given by (4) above. The theoretical dispersion in group velocity is small enough to account for the lack of observed dispersion in body waves. Other viscoelastic theories were analyzed but no similar agreement with experimental data has been obtained.

Electromagnetic Oscillations (H. Benioff and F. Press)

The program of recording electromagnetic oscillations in the period range 0.2 to 100 seconds, begun by Benioff and mentioned in our previous report, has been continued. Additional recorders were installed at Palomar and Mount Wilson. Comparisons of recordings from these stations with Pasadena have demonstrated the existence of nearly sinusoidal disturbances which are simultaneous in time and identical in form at the three sites. These disturbances have periods ranging from

Fig. 2 – Short-period electromagnetic oscillations recorded at Pasadena; time marks at intervals of one minute

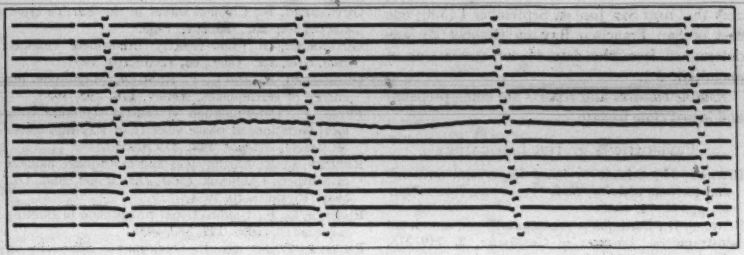

FIG. 3 – Long-period electromagnetic pulse with superposed short-period oscillations recorded at Pasadena; time marks at intervals of one minute

0.5 to 20 seconds. Disturbances of longer period consisting of simple impulses frequently with short period nearly sinusoidal oscillations superposed are also observed simultaneously and of identical form at the three stations. A diurnal effect on the occurrence of these disturbances has been noted and is different for different period ranges. In addition, an annual variation is indicated with a minimum of activity in November–December for all periods. An example of the short period sinusoidal oscillations is shown in Figure 2. Figure 3 is a reproduction illustrating the long-period impulsive type with superposed short-period oscillations.

KERN COUNTY AFTERSHOCKS (STUDENT RESEARCH)

Allan Sanford studied seismograms for the first five hours following the major Kern County earthquake of July 21, 1952. Because of overlapping recordings the aftershocks in that interval cannot be located with precision; but he was able to find approximate epicenters for 20 shocks of magnitude 4 and over; all are on the southeast side of the surface trace of the White Wolf fault, as was previously found for all other aftershocks within 36 hours after the main shock.

SEISMICITY IN GENERAL

During 1955 activity was at a low level. Preliminary listing of shocks assigned magnitudes of 7 or over includes only 13 shallow shocks, 2 intermediate and one deep. The largest, on February 27, had a unified magnitude of about $m = 7\frac{1}{4}$, corresponding to about $M = 7\frac{3}{4}$ on the old scale.

OBSERVATIONS OF LOCAL AND DISTANT EARTHQUAKES (C. F. RICHTER)

Local seismicity—In Southern California and Owens Valley only two shocks of magnitude over 4.9 occurred during 1955: March 2, near San Lucas (magnitude 5.1); December 16, near Brawley (magnitude 5.4). Other totals are: magnitude 4.0–4.9, 7 in Kern County, 18 elsewhere; magnitude 3.0–3.9, January 1–November 30 only, 53 in Kern County, 75 elsewhere.

'Kern County' here indicates only the area of aftershock activity consequent on the earthquakes of 1952. This activity, though decreasing, continues within the sharp geographical limits set in previous years, except for (a) a shock of magnitude 4.5 on May 28, south of Weldon and well to the northeast of the aftershock group, and (b) one of magnitude 3.9 on November 22, well recorded and located with our maximum accuracy in the San Andreas fault zone west of Gorman. The latter is almost the only shock recorded since the establishment of the Seismological Laboratory which can be attributed with any confidence to this part of the San Andreas fault, and not to some subsidiary or branch fault.

A sequence of shocks originating close to Brawley on December 16–17 caused some damage there, largely to structures injured in previous earthquakes. The first shocks of this sequence were small, followed by larger ones up to the largest (magnitude 5.4); the aftershocks decreased irregularly, with a secondary maximum, including a shock of magnitude 4.3, after 14 hours; thereafter the activity decreased sharply. In the past this type of sequence has characterized the Imperial Valley area and has seldom appeared elsewhere in Southern California, where the normal pattern is that of a small foreshock and a gradually decreasing aftershock series. It is believed caused by generally smaller tectonic block structure in the Imperial Valley area.

No shocks with magnitude approaching 6 occurred during 1955 in the entire region including and surrounding California. The largest was prob-

ably that near San Jose on September 4 (5.8); one east of San Francisco Bay on October 23 was determined from the data of our stations as of magnitude 5.5.

Routine bulletins and reports are being prepared and issued close to date.

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Selected List of Russian References of Sedimentology

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Abstract—American geologists and geophysicists have almost no knowledge of Russian research, whereas Soviet geologists and geophysicists are in general well informed of foreign literature. A selected list of Russian references on sedimentology is included in the hope of creating new interest in reading Russian scientific literature.

The importance of keeping abreast of scientific literature is recognized by all scientists, but unfortunately it generally is not possible for most of us to keep pace with current domestic publications as pointed out by K. O. Emery (Trends in literature on sedimentology, *J. Sed. Petrology*, **21**, 105–108, 1951), much less those of foreign countries having difficult languages. Numerous difficulties arise when one attempts to check Soviet research; these include the language barrier, the poor distribution of their publications, and the frequent changing of journal names. Another barrier in our knowledge of Soviet science was created in 1947, when the Soviet Government ceased to publish an abstract or even an index in a non-Russian language of Soviet scientific literature. As a result of these problems very little is known about Soviet research in the field of sedimentology, particularly in the post-war years. This lack is reflected in the small number of citations to Russian articles in American publications.

In order to determine the actual number of citations to Soviet literature in the field of geophysics, the references listed for articles in volume 32 (1951) of the *Transactions, American Geophysical Union* were scanned and the results tabulated in Table 1. For comparison, volumes 77, 78, and 79 (1951) of the *USSR Academy of Sciences Reports* (*Doklady Akademii Nauk SSSR*), were also checked. Since this Soviet journal embraces many branches of science, only geological and geophysical subjects were checked. The percentage of foreign references in the *USSR Academy of Sciences Reports* is more than three times as large as for the *Transactions*, and approximately ten per cent of the references cited in the former journal are those published in English, whereas the percentage of Russian references in the American journal constitute about one-half of one per cent. While the results show conclusively that the Russians are much better informed of our work, they may be even more informed than shown by Table 1 for at least two reasons: (1) The Russians have a tendency to keep the number of foreign citations (particularly those in English) to a bare minimum, and (2) if any other American journal had been selected for such a check, the number of citations to Soviet work would have been negligible. Nevertheless, the results lead to one main conclusion: Russian scientists are much better informed of our work than we are of theirs.

Since English-speaking scientists are almost completely unfamiliar with recent research in sedimentology within the Soviet Union, a selected list of references is presented here in the hope that better use will be made of Russian literature in our own research. Most of the references listed below were obtained from the *Guide to Russian Scientific Periodical Literature*, published by the Brookhaven National Laboratory, Upton, New York. Unfortunately this organization stopped distribution early in 1952 after publishing four volumes. References were also obtained from several other sources but all were incomplete and did not include references later than 1952. Some later references were selected from recent copies of Soviet periodicals. Since many of the references were taken from various sources there may be variations in spelling and in exact translations of

TABLE 1 – *Comparison between articles published in an American journal and a Soviet journal for the year 1951*

Item	Transactions, American Geophysical Union	USSR Academy of Sciences Reports
Number of pages	755	523
Number of articles	112	148
Number of Russian references	4	628
Number of English references	789	83
Number of French references	13	39
Number of German references	32	32
Other foreign references	12	51
Total number of foreign references	61	205
Total number of all references	850	833
Average number of pages per article	6.8	3.5
Average number of references per article	7.6	5.6
Per cent of foreign references	7.2	24.6
Per cent of English references in Russian journal	...	9.9
Per cent of Russian references in American journal	0.48	...

titles. All references marked with an asterisk indicate that a translation has been made and is on file at the Library of Congress. All references listed are available in the United States. Most large libraries have a few Russian periodicals, and some libraries (such as the University of California Library at Berkeley) have nearly all of the references listed. The Library of Congress probably has all references presented here.

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Notes & Personalia

Notes

CORRIGENDA—In the paper by Alfred J. Zmuda appearing in the February, 1956, issue, equation (14) on page 10 should read

$$q \gg n + 1$$

In the article by Yasukazu Saito on page 41 of the February, 1956, issue there is a radical in the first equation in the left-hand column under which the notation is missing. The notation should be $n\Delta T$ such as one sees almost directly above and in the denominator in the term to the right.

In the list of new members on page 131 of the February issue of 1956, left column, line 20, Snelson's address should be 2535 Piedmont Avenue, Berkeley 4, California.

ANTARCTIC OPERATIONS FOR IGY, 1955–1956—During November, 1955, ships of Naval Task Force 43 departed from the United States to conduct Operation Deepfreeze I, a preliminary phase of the Antarctic program planned by the U. S. National Committee for the International Geophysical Year. Three icebreakers, three cargo vessels, an oil tanker, and two oil barges proceeded to New Zealand and left there in December to take up picket positions along a flight line to McMurdo Sound. Four long-range planes successfully landed on the ice of McMurdo Sound. The ships of the Task Force then proceeded to set up two base stations on the Ross Sea.

Little America V was established at Kainan Bay, about 40 miles west along the edge of the Ross Ice Shelf from the site of the former Little America Stations. Nearly completed, the station now houses 70 wintering-over personnel. The Williams Air Operations Facility, at Hut Point on Ross Island in McMurdo Sound, is in the final stages of construction. This support base for the airlift to the South Pole accommodates 93 personnel during the present winter season.

While the construction of the stations and the unloading of the cargo ships was in progress, preliminary operations for the campaigns of the 1956–57 Antarctic summer were launched. A party of light oversnow vehicles reconnoitered a trail from Little America V toward the site of the proposed Byrd Station in Marie Byrd Land. The trail reconnaissance party marked 380 miles of their 600 mile route before turning back because of mechanical trouble with their vehicles. Two cache-laying sled swings laid out fuel depots on the trail for use during the establishment of the station commencing in October, 1957.

Before returning to New Zealand in mid-January, the four long-range planes based at McMurdo Sound completed reconnaissance flights over the polar plateau following the course to be utilized by aircraft in establishing the Pole Station in the operating season of 1956–57.

Among the matériel transported to the Antarctic by the Task Force was equipment to set up and operate the Byrd and Pole Stations. Cached respectively at Little America and McMurdo Sound, this cargo will be carried into the station sites early in the 1956–57 operating season. An IGY Representative is wintering-over at each of the coastal stations to monitor the scientific supplies and to accompany the construction personnel for the establishment of these stations. These two IGY Representatives will conduct experimental meterological research and meteor and aurora studies during the long winter, as well as a limited program in snow and ice physics.

Additional activities conducted during Operation Deepfreeze I included a survey of the east coast of Victoria Land for a site for the establishment of a joint New Zealand – U. S. station to be set up next year. One of the icebreakers is presently cruising along the Knox Coast in East Antarctica and the Filchner Ice Shelf on the Weddell Sea to reconnoitre locations for two additional stations to be established next year. IGY Representatives have accompanied these reconnaissance cruises, as well as overseeing the unloading and caching of IGY supplies at the present station sites.

Limited scientific programs were pursued during the operation: cosmic ray apparatus was located on one of the ships and has been functioning since its departure from the U. S.; hydrographic and oceanographic investigations have been pursued on a routine basis during the operation; the ships and the shore stations are continuing meteorological observations to which the stations will soon add upper air soundings.

Richard E. Byrd, Rear Admiral and Officer in Charge, U. S. Antarctic Programs, returned to the United States from the Antarctic on March 13, concluding his fifth mission to the continent. G. L. Ketchum, Deputy Commander Task Force 43, and Paul A. Siple, veteran Antarctic expert have also recently returned. George Dufek, Rear Admiral and Commander of Task Force 43, has remained in the area aboard the USS *Glacier*, the Navy's newest icebreaker, which is scheduled to make a reconnaissance of the eastern Antarctic coast, including possible sites for the planned USNC-IGY stations at Knox Coast and the Weddell Sea.

NATIONAL SCIENCE FOUNDATION GRANTS—The National Science Foundation has recently announced 164 grants totaling $3,240,500 during the quarter ending December 31, 1955. Among these are ones to Wesleyan University for critical tectono-metamorphic problems (John L. Rosenfeld, $16,800); Massachusetts Institute of Technology for cosmic-ray research (Bruno B. Rossi, $25,100); and University of Washington for the distribution of some minor constituents of sea water (Thomas G. Thompson, $13,500).

CONFERENCE ON THEORETICAL GEOPHYSICS—A Conference on Theoretical Geophysics was held at the National Science Foundation, February 1–3, 1956, under the joint sponsorship of the Foundation and the Carnegie Institution of Washington. The purpose of the Conference was to consider the current status of knowledge and study in theoretical geophysics in the United States and to encourage increased activity in theoretical geophysics. Also discussed was a possible plan

for the establishment of one or more strong institutes of theoretical geophysics in the United States. John von Neumann of the Institute of Advanced Study at Princeton and member of the U. S. Atomic Energy Commission served as Chairman.

SUMMER INSTITUTES OF SCIENCE—The program that the National Science Foundation instituted on an experimental basis in 1953 and continued subsequently on an enlarged scale for summer institutes of science is proceeding for the summer of 1956 on a larger scale than hitherto, and it is contemplated that it will be continued in 1957. These are in general of two different sorts, (1) those intended for high school science teachers and (2) those intended for college science teachers. Courses for high school science teachers will be given during the coming summer at Alabama College (general), American University (physical sciences), University of Arkansas (natural sciences), University of Indiana (biology), Iowa State Teachers College (mathematics), Marshall College (physical sciences), Montana State College (chemistry), Oak Ridge Institute of Nuclear Studies (physical sciences), Pennsylvania State University (general), University of Rochester (physics), University of Utah (biology), Wesleyan College, Connecticut (general), Williams College (mathematics), and University of Wyoming (physics). The courses for college science teachers are being given at Argonne National Laboratory (nuclear energy), Cornell (botany), Indiana University (chemistry), University of Michigan (mathematics), Montana State College (chemistry), Oak Ridge Institute of Nuclear Studies (physical sciences), Oregon State Teachers College (chemistry), University of Utah (biology), Williams College (mathematics), Wisconsin State College (astronomy), and University of Wyoming (physics). Interested persons should address the appropriate division or department of the university or write direct to the National Science Foundation, Washington 25, D. C.

In addition to these institutes sponsored by the National Science Foundation, a large number of colleges and universities will have special institutes for various aspects of the physical sciences during the coming summer.

CIVIL SERVICE EXAMINATIONS FOR GEOPHYSICISTS—The Board of Civil Service Examiners has announced an examination for geophysicists in the options of Earth physics, geomagnetism, and seismology in grades ranging from GS-5 to GS-15 (salary range $4,345 to $11,610). The positions vacant are in the U. S. Coast and Geodetic Survey and various other Federal agencies in Washington, D. C., and throughout the United States, with a few positions to be filled in territories and possessions of the United States overseas. Interested persons should write to the Board of Civil Service Examiners, U. S. Coast and Geodetic Survey, Washington 25, D. C. No closing date is announced for the examination.

BRAZILIAN OCEANOGRAPHIC-SURVEY VESSEL LOST—The *Ungava*, fitted out for the Institute of Oceanography and Marine Biology of the University of Sao Paulo, Brazil, during 1955 under a grant from the Rockefeller Foundation, was lost by fire on November 11, 1955, while at sea on a voyage from Cananeia to Santos. She was the most completely equipped vessel for oceanographic research in Latin America.

PROGRESS OF THE U. S. GEOLOGICAL SURVEY—In the Annual Report of the U. S. Geological Survey for fiscal year 1955, it is pointed out that new heights of achievement in topographic mapping knowledge of the nation's water supplies, geologic interpretation, and value of royalties from mineral and petroleum leases on public lands were attained. Now completing its 77th year of existence, its program is still far from complete; but in 1955, 2669 topographic maps were printed for the first time or reprinted. The Sixth Edition of the Status of Topographic Mapping is now available and may be secured from the Map Information Office of the Survey. The compilation of summaries of streamflow records from 1888 to 1950 is progressing and is now 57 per cent complete. Streamflow records are currently collected at 6800 locations. Five hundred ground-water projects are currently under investigation, and 64,000 samples of natural waters were analyzed for chemical quality.

SOVIET OCEANOGRAPHIC EXPEDITION—The diesel electric ship *Ob* is now on a 20,000-mile cruise on oceanographic research which will carry it to the southern parts of the Indian Ocean along the east coast of the Antarctica, to New Zealand and Australia into the Western Indian Ocean, and returning to Russia by way of the Atlantic.

TOPOGRAPHIC MAP COLLECTION ILLUSTRATING LAND FORMS—From among its many topographic maps, the U. S. Geological Survey has selected a set of 100 to illustrate a wide variety of physiographic features. The new assembly replaces a similar selection that had been in use for a number of years. The set may be secured at nominal cost through the Survey from either its Washington, D. C., or Denver offices.

NEW OBSERVATORY IN PAKISTAN—The new Geophysical Observatory at Quetta now comprises four buildings and has a staff of 20 scientists. This observatory was undertaken in connection with the United Nations program of technical assistance and includes a seismological section and a section on atmospheric physics, which is concerned also with the water economy of western Pakistan.

MEETING OF UNESCO'S ADVISORY COMMITTEE ON MARINE SCIENCES—A meeting of scientists from nine countries, Australia, Denmark, France, India, Japan, Mexico, the United Kingdom, the United States, and the U.S.S.R., was held in Tokyo in October, 1955, under the auspices of UNESCO's Advisory Committee on Marine Sciences. The recommendations of the meeting emphasize the need for cooperation in research in the Indian Ocean, along the east coast of Asia, and the coasts of South America. The Committee further recommended the creation of more fellowships and travel grants for workers in the marine sciences and approved a training course to be given in Cuba in 1956 under UNESCO auspices. Plans were laid for the meeting in 1956 to be held somewhere in Latin America.

SURVEY OF THE NORTH PACIFIC OCEAN—During the summer of 1955, agencies and organizations from the United States, Canada, and Japan carried on an integrated oceanographic survey referred to as NORPAC. This program was outlined at our annual meeting

in 1955, and an abstract of this presentation appears in the June, 1955, issue of the *Transactions*, page 507. The work was carried out essentially as planned. At intervals of from 20 to 200 miles, water samples and temperatures were taken from the surface to depths varying up to 6000 meters. Some of the vessels were provided with sounding equipment to keep a record on the depth of the ocean, and measurements were taken of transparency surface currents and the Earth's magnetic field. The program also involved the biological aspects, and specimens were taken of zooplankton and phytoplankton at depths of 100 to 1000 meters, and observations were made on birds, fish, and other oceanic life. Processing of the hydrographic data is under way, and results should begin to be available in the spring of 1956.

NEW GEOPHYSICAL JOURNAL—The Science Council of Japan has added the *Japanese Journal of Geophysics* to its list of publications with volume 1, number 1, bearing the date of May 1954, and volume 1, number 2, the date of May 1955. No. 1 has about 80 pages and includes two papers, one by Kikkawa on radioactive springs and one by Tao on radio-wave propagation. These are listed respectively in the Bibliographies of Hydrology, and Terrestrial Magnetism and Electricity in this issue.

WORLD CONFERENCE ON EARTHQUAKE ENGINEERING—The Earthquake Engineering Research Institute and the University of California are making arrangements for a World Conference on Earthquake Engineering to be held at the University of California in Berkeley, June 12–16, 1956. Interested persons should write to the Secretary, Ray W. Clough, Division of Civil Engineering, University of California, Berkeley 4, California, for further details.

RESEARCH ASSOCIATESHIPS AND ASSISTANTSHIPS IN UPPER ATMOSPHERE PHYSICS AT UNIVERSITY OF MARYLAND—These positions are now available for qualified applicants. Research associate positions are intended for physicists holding doctorates who desire to initiate and undertake programs on some phase of upper atmosphere physics using high-altitude rockets as research tools. They carry a minimum salary of $5200. Research Assistantships are intended for predoctorate students with full-time salary based on $300 per month. Further information can be secured from the Physics Department of the University of Maryland, College Park, Maryland, Attention: Upper Atmosphere.

FOUTH MEETING ON HYDRAULICS OF THE SOCIÉTÉ HYDROTECHNIQUE DE FRANCE—This meeting will be held in Paris, June 13–15, 1956, with a trip to Saint-Malo on June 10–12 and a trip to Argentat and Cambeyrac on June 16–17. The program this year is on the theme of the energy of the sea. Some 70 papers relative to mechanical energy models, utilization, and thermal energy will be presented. Interested persons should get into touch with Société Hydrotechnique de France, 199, Rue de Grenelle, Paris (7e), France.

GUENTER LOESER MEMORIAL LECTURE TO BE GIVEN IN BOSTON, MASS., JUNE 29, 1956—The second Guenter Loeser Memorial Lecture will be presented at 2:00 p.m. on June 29, 1956, in the Charter Room of the New England Mutual Building, Boston, Mass., on the subject of Phenomenological Considerations of the Interruption Theory of Line Broadening, by Robert G. Breene, Jr. This lecture series was established by the Geophysics Research Directorate of the Air Force Cambridge Research Center in honor of Dr. Guenter Loeser, an outstanding geophysicist of the Directorate who gave his life in a field experiment.

PROGRESS TOWARD THE PURIFICATION OF SEA WATER—Progress toward the producing of fresh water from sea water on an economical basis is developing according to a recent report of the U. S. Department of the Interior, and estimates indicate that large-scale conversion of sea water is now approaching the maximum existing costs of municipal water in the United States although it is still several times higher than water supplies used for irrigation purposes. The use of brackish waters instead of sea water improves the economy of the efforts. Investigations are being carried out using membranes, distillation, freezing, and other techniques.

CONFERENCE ON THE PROBLEMS OF THE HUMID TROPICAL ZONE—A Conference on Humid Tropical Regions, which cover almost one-third of the land area of the Earth, was held in Colombo, Ceylon, March 19–21, 1956. The Conference will be followed by the efforts of a work group of twelve which will be engaged in the setting up of a preliminary program of specific activities. The Conference was sponsored by UNESCO.

DEVELOPMENT OF THE COLORADO SCHOOL OF MINES—Extensive plans have been laid for the development and expansion of the Colorado School of Mines under a plan that is referred to as the "Horizon Plan." The program contemplates the expenditure of about $20,000,000 in capital funds and $450,000 in annual funds to augment state support of the school, this development to take place over a period of 20 years. The plan contemplates the expansion of physical facilities, extension of areas of study, as well as improved circumstances for faculty members and aid to students.

THE FIFTH NATIONAL CLAY CONFERENCE TO BE HELD AT URBANA, ILLINOIS, OCTOBER 8–10, 1956—This Conference, sponsored by the Clay Minerals Committee of the National Academy of Sciences—National Research Council under the chairmanship of R. E. Grim of the University of Illinois, will include contributed papers on subjects related to clay mineralogy and technology. Titles for possible inclusion in the program should be received by May 1, with brief informative abstracts by June 15. Interested persons should get into touch with W. F. Bradley, Illinois Geological Survey, Urbana, Illinois.

FELLOWSHIPS OF NATIONAL SCIENCE FOUNDATION—The National Science Foundation has recently announced the award of 775 predoctoral graduate fellowships for the academic year 1956–57. These were selected from 2892 applicants. Honorable mention was accorded to 1366 applicants. In addition, 80 postdoctoral fellowships were awarded.

In the predoctoral group 40 were in the Earth sciences, 165 in physics, 109 in engineering, 182 in

chemistry, 67 in mathematical sciences, and 11 in agriculture. In the postdoctoral group five were in the Earth sciences, 19 in chemistry, 13 in mathematics, nine in physics and astronomy, and two in engineering.

Predoctoral fellowships carry stipends of $1400 for the first year, $1600 for intermediate years, and $1800 for the terminal year of graduate study. Postdoctoral fellowships carry a stipend of $3400. All fellowships include additional allowances for dependents, tuition, and other normal expenses.

It is anticipated that the program will continue in 1957–58. Announcements concerning this will be made about October 1 with respect to predoctoral fellowships and July 15 with regard to postdoctoral fellowships.

Personalia

ARTHUR A. BAKER, who has been with the U. S. Geological Survey since 1921, has been designated as Associate Director of the Survey.

HENRY B. BIGELOW, oceanographer and Professor Emeritus of Harvard University, was honored on the occasion of the 25th anniversary of the Woods Hole Oceanographic Institution, which Institution he helped to found. He served as its first Director from 1930–1940. A collection of 48 original scientific contributions designated as the Bigelow Volume was prepared by his colleagues and former students. The volume is a 500-page supplement to the periodical *Deep Sea Research*.

M. CLIFFORD BOYER has resigned as Associate Professor of Mechanics and Hydraulics at the State University of Iowa to take up duties in charge of hydrologic investigations for the Indiana Flood Control and Water Resources Commission.

KENNETH L. COOK, Professor and Head of the Department of Geophysics at the University of Utah, has been appointed Chairman of the Mining, Geology, and Geophysics Division and Director *ex officio* of the American Institute of Mining, Metallurgical, and Petroleum Engineers.

ROYAL W. DAVENPORT, Chief of the Technical Coordination Branch of the Water Resources Division of the U. S. Geological Survey, has retired after more than 45 years of Government service, most of which time was devoted to work on the water problems undertaken by the U. S. Geological Survey.

RICHARD R. DOELL, Lecturer in Geophysics at the University of Toronto, who recently received his doctorate at the University of California, has been appointed Assistant Professor in the Department of Geology and Geophysics of the Massachusetts Institute of Technology.

PHILIP C. DORAN, Captain, U. S. Coast and Geodetic Survey and Chief of the Division of Geodesy, has retired after serving nearly 33 years with the Survey. He has accepted a position with a subsidiary of the California Texas Oil Co. on geodetic control work in Western Australia.

NICHOLAS V. FEODOROFF, Associate Professor of Civil Engineering of Manhattan College, has been appointed a member of the Committee on Fellows of the New York Academy of Sciences. He has also recently been reelected Chairman of the Section of Mathematics.

ALBERT W. FRIEND, Technical Consultant of Bala-Cynwyd, Pennsylvania, was recently given the second annual award of the National Electronics Conference for his paper, The Use of Powdered Iron in Television Deflecting Circuits.

JOSEPH J. GEORGE, Superintendent of Meteorology for Eastern Airlines and Chairman of the President's Advisory Committee on Weather Control, was recently given the first annual award of the American Meteorological Society for outstanding contributions to applied meteorology.

HERBERT HOOVER, JR., Under Secretary of State, has been awarded the Kemp Medal of Columbia University for distinguished service in geology.

ORSON W. ISRAELSEN is now in Iran serving as consulting engineer on irrigation and drainage problems. Only recently he completed a year as Professor of Irrigation Engineering at the University of Roorkee in India.

THOMAS B. NOLAN, who has been Assistant Director of the U. S. Geological Survey since December, 1944, has been appointed Director of the Survey. The appointment was made by President Eisenhower and now awaits Senatorial approval.

CHARLES PIERCE, Captain in the U. S. Coast and Geodetic Survey, has been designated as Chief of the Division of Geodesy of the Survey.

NORRIS W. RAKESTRAW, Head of the Chemistry Division of the Scripps Institution of Oceanography, has been given the $1000 James Flack Norris Award of the American Chemical Society for outstanding achievement in the teaching of chemistry.

ROGER R. REVELLE, Director, Scripps Institution of Oceanography, has been appointed by the Director-General of UNESCO to serve on a newly established International Advisory Committee on Marine Sciences.

HAROLD C. UREY of the Fermi Institute for Nuclear Studies, University of Chicago, has been elected an Honorary Fellow of the Indian Academy of Sciences. He will spend the academic year, 1956–1957, as Eastman Professor at Oxford University in England.

GILBERT F. WHITE, Professor of Geography at the University of Chicago, has been designated by the Secretary of State as one of the 16 new members of the U. S. National Commission for UNESCO.

WILLIAM E. WRATHER, Director of the U. S. Geological Survey since 1943, has recently retired.

ISAAC MONROE CLINE, retired meteorologist, died in New Orleans, August 3, 1955, at the age of 94. He was born in Madisonville, Tennessee, took his baccalaureate degree at Hiwassee College in 1882, and his A.M. in 1885. He received his M.D. from the University of Arkansas in 1885, and a Ph.D. from Texas Christian University in 1896. He was honored by Tulane University with a Doctor of Science degree in 1934. He began his work with the Weather Service, which was then in the Signal Corps of the U. S. Army in 1882, served at various posts in the West Gulf States and adjacent areas, and rose to the position of principal meteorologist with the Weather Bureau before his retirement in 1935. He was active in various scientific groups and was one of the pioneers in the work on the relationship of storm tides to the movement of tropical hurricanes, and did some of the first studies of the structure and movement of storms. He is known also for his flood prediction work in the Mississippi Valley, especially during the flood of 1927, and for this work was commended by President Hoover. He had been a member of AGU since 1934.

GERRIT DUYS, JR., research assistant on the staff of the Woods Hole Oceanographic Institution specializing in geophysics and underwater sound, died March 16, 1955, at the age of 31. He was born at Great Neck, New York, and studied at Columbia University in 1941–1942 and took his baccalaureate degree at the University of Massachusetts in 1948. Since that time he was on the staff of the Woods Hole Oceanographic Institution. From 1944 to 1946 and during the summer of 1947 he was also engaged on work at the Institution. He had been a member of AGU since 1950.

NEAL J. HEINES, amateur astronomer of Paterson, New Jersey, died August 20, 1955, at the age of 63. He was born at Rotterdam, The Netherlands, and in his chosen avocation of astronomy he was self-taught. He was active in the American Association of Variable Star Observers and contributed substantially to the war effort in connection with that work. At one time he taught at Paterson State Teachers College and at Hope College in Grand Rapids, Michigan. He had been a member of AGU since 1937.

ERIC HINTON, Manager of the Bowater Power Company at Deer Lake, Newfoundland, died May 7, 1955, at the age of 54. He was born at Warwick, England, and was educated as a civil engineer in England before moving to Newfoundland to participate in the original construction of the power development at Corner Brook Paper Mills where he continued on the operating staff as Hydraulic Engineer. He became Manager of the Hydro-Electric Department in 1942. He had been a member of AGU since 1938.

PAUL VINCENT HODGES, Hydraulic Engineer for the Corps of Engineers with Headquarters at Denver, Colorado, died February 24, 1955, at the age of 71. He was born at Monroe, Wisc., and took his baccalaureate degree from the University of Wisconsin in Civil Engineering. From 1914 to 1931 he was with the U. S. Geological Survey Water Resources Branch, and from 1931 to 1942 with the U. S. Indian Irrigation Service. He entered the service of the Corps of Engineers in 1942. He had been a member of AGU since 1942.

GERHARD ERUMBACH, Director of the Institute of the Dynamics of the Earth and Earthquake Observations of Jena, Germany, died December 23, 1955.

JAMES BERNARD MACELWANE, President of the American Geophysical Union and Dean of the Institute of Technology of St. Louis University, died February 15, 1956. A brief biography appears on the opening pages of this issue.

LUDGER BENEDIKT MINTROP, University Professor of Essen, Germany, died January 1, 1956, at the age of 75. He was born in Essen and studied at the University of Berlin and the University of Technology at Aachen. In 1905 he became Assistant Professor of the Geophysical Branch of the University of Technology, subsequently teaching at the Geophysical Institute of Göttingen, Bochum Mining School, and the University of Breslau. From 1921 to 1934 he served as the President of the Seismos Company in Hannover. In 1946 he returned to the Technical University at Aachen as Professor of Applied Geophysics. He had been a member of AGU since 1952.

NICHOLAS ANTHONY ROSE, Ground-Water Geologist with Lockwood and Andrews of Houston, Texas, died July 16, 1955, at the age of 45. He was born at Nashville, Tennessee, and took his baccalaureate degree from Vanderbilt University in 1933. After a brief tour of duty with the U. S. Geological Survey, he took up duties as a geologist with the Tennessee Valley Authority where he continued until 1939. He returned to the U. S. Geological Survey at that time and continued until 1945, at which time he entered the staff of Lockwood and Andrews as a Ground-Water Geologist. He had been a member of AGU since 1941.

E. SUCKSDORFF, in charge of magnetic activities of the Finnish Central Meteorological Observatory and Secretary of the Finnish National Committee for the International Geophysical Year, died October 19, 1956, at the age of 57.

Union, Section, and Committee Activities

ANNUAL MEETING OF PACIFIC SOUTHWEST REGION—The annual meeting of the Pacific Southwest Region was held January 16–17 at the University of California in Los Angeles with about 100 in attendance. On the evening preceding the meeting continuing into the first meeting day, Los Angeles experienced a 7½ inch rainfall which cut down attendance substantially, and it was necessary to cancel two of the papers because of the circumstances resulting. It was none the less considered to have been a highly successful meeting, and as the address at the banquet concerned the problems of air pollution, some thought was expressed that AGU should have a section particularly concerned with the atmosphere as a resource. Sixteen papers bearing chiefly on hydrology and meteorology were presented.

MEETING OF THE GEOPHYSICAL SOCIETY OF HAWAII, NOVEMBER 15–18, 1955—The Geophysical Society of Hawaii, which serves jointly as the regional group of the American Geophysical Union and the local group of the American Meteorological Society, had its meeting in Honolulu as scheduled, November 15–18, 1955. One hundred and three persons were in attendance, and 75 papers were presented. Ten of the papers composed a symposium under the chairmanship of Thomas S. Moorman, Jr., Brigadier General, U. S. Air Force, on the subject of weather reconnaissance during the International Geophysical Year. Following registration on the morning of November 15, the meetings were officially convened during a luncheon at the Reef Hotel, the meeting headquarters. Alan H. Shapley of the Central Radio Propagation Laboratory, National Bureau of Standards, and Vice-Chairman of the U. S. National Committee of the IGY, discussed the IGY program in the Pacific area. Formal sessions were held in fields of research such as meteorology of the jet stream, cloud physics, oceanography, tropical meteorology, synoptic meteorology, etc. Field trips were held to points of geophysical interest, including the volcano on the Island of Hawaii, and various laboratories in the Islands that are active in geophysical research.

Thomas S. Austin
Secretary-Treasurer, Geophysical Society of Hawaii

Special Announcements

OFFICE OF AMERICAN GEOPHYSICAL UNION TO MOVE—It is anticipated that in June the office of the American Geophysical Union will be moved to the new building of the American Association for the Advancement of Science at 1515 Massachusetts Ave., N.W., Washington 5, D. C. Rent-free quarters have been occupied by AGU in the Administration Building of the Carnegie Institution of Washington at 1530 P St., N.W., Washington, D. C., for over nine years and prior to that in the Carnegie Institution's Department of Terrestrial Magnetism at 5241 Broad Branch Road, N.W., Washington, D. C., for 22 years. The Union owes a great debt of gratitude to the Carnegie Institution of Washington for this long period of provision of quarters, which has been a major factor in the development of the Union and of Geophysics through these many years. At the building of the American Association for the Advancement of Science it is anticipated that we will occupy Rooms 315, 316, 317, and 318 on the third floor.

HYDROLOGIC SYMPOSIA TO BE HELD AT DIJON, FRANCE, IN SEPTEMBER, 1956—The International Association of Hydrology, IUGG, is planning symposia to be held in Dijon, France, September, 1956. The subjects are: the hydrology of floods, phenomena of infiltration, and evaporation. Also planned in connection with the meeting is an assembly of the Council of the Association. Interested persons should get in touch with H. G. Wilm (New York State College of Forestry, Syracuse 10, New York), President, Section of Hydrology, AGU, who heads the U. S. National Committee of the Association of Hydrology, or Professor L. J. Tison (61, rue des Ronces, Gentbrugge, Belgium), Secretary of the International Association. Another event to be commemorated at this meeting is the 100th anniversary of the fundamental studies by Darcy.

PACIFIC NORTHWEST REGIONAL MEETING TO BE HELD IN NOVEMBER IN THE SEATTLE-TACOMA AREA—It is planned to hold the Third Annual Meeting of the Pacific Northwest Regional Group in the Seattle-Tacoma area in November, 1956. Robert T. Beaumont (U. S. Soil Conservation Service, 209 S.W. Fifth Avenue, Portland 4, Ore.) has been designated as Chairman of the Program Committee, and other organizational details are now being worked out. Interested persons should get into touch with him or with Regional Chairman Milton R. Sachs (2157 N.E. Tillamook St., Portland, Ore.) or with Secretary-Treasurer Vail P. Schermerhorn (U. S. Weather Bureau, 320 Custom House, Portland 9, Ore.).

PACIFIC SOUTHWEST REGIONAL MEETING IN FEBRUARY, 1957—The Annual Pacific Southwest Regional meeting will be held in Sacramento, either February 7–9 or February 14–16, 1957. Harlowe M. Stafford (3360 Fair Oaks Boulevard, Sacramento 21, California) is acting as General Chairman for the meeting, and Harvey O. Banks (431 Ross Way, Sacramento 21, California) will serve as Program Chairman. The Program Committee is now in the process of organization. Jerome van de Erve (U. S. Weather Bureau, Box 2002, Sacramento, California) will serve as Chairman for the Program in Meteorology. Fred Strauss will serve as Chairman of the Committee on Local Arrangements.

ELEVENTH GENERAL ASSEMBLY OF IUGG—The Eleventh General Assembly of the International Union of Geodesy and Geophysics will be held at the University of Toronto, Toronto, Ontario, Canada, August 5–17, 1957. A note from the Canadian National Committee indicates that all geophysicists and students of geophysics will be welcome to attend and to bring members of their family. Arrangements are being made for accommodations of delegates in University residences and in downtown hotels. University dining halls will be open. Those who desire to attend should advise the office of AGU in order that their names may be formally listed in the list of delegates, participants, and guests, which in due course will be sent to the Canadian National Committee. Questions concerning reservations shold be sent to Prof. J. Tuzo Wilson (Geophysics Laboratory, 49, St. George St., University of Toronto, Toronto 5, Canada), who is Chairman of the Toronto Arrangements Committee for the IUGG meeting.

With regard to the scientific program and the submission of papers, those who are U. S. citizens should send these to the office of the American Geophysical Union or the appropriate Section Secretaries, or in case you are dealing with international officers direct, please send carbon copies of your communications to the office of AGU.

AVAILABLE REPRINTS

In addition to the back numbers of the *Transactions* of AGU still generally available as listed in the *Transactions* of December 1954, Part 2 (directory), pages 129–130, reprints of the material listed below are also available.

Item	Title	Reference	Price	
			1 to 12 copies	13 or more copies
1	Symposium, Interior of the Earth	v. 35, pp. 47–98, 1954	$1.00 each	$0.80 each
2	Origin and Development of the American Geophysical Union, by Jno. A. Fleming	v. 35, 1–46, 1954	0.25 each*	0.15 each
3	Colloquium on Plastic Flow and Deformation within the Earth	v. 32, pp. 497–543, 1951	1.00 each	0.80 each
4	Symposium on Dynamics of Land Erosion	v. 22, pp. 236–320, 1941	1.00 each	**
5	Symposium on Tectonics of the Crust	v. 21, pp. 153–177, 1940	0.75 each	**
6	Symposium on Geophysical Prospecting	v. 20, pp. 241–303, 1939	1.25 each	**
7	Symposium, The Surface and Subsurface Exploration of Continental Borders	v. 19, pp. 781–826, 1938	1.00 each	0.80 each
8	*Transactions* of 1933, Papers of General Assembly	v. 14, pp. 1–40, 1933	0.40 each	**
9	*Transactions* of 1933, Papers of Section of Meteorology	v. 14, pp. 67–108, 1933	0.40 each	**
10	*Transactions* of 1933, Papers of Section of Hydrology	v. 14, pp. 337–521, 1933	1.50 each	**

* A single copy will be supplied without charge to each member applying.
** Very limited number of copies available.

Orders and inquiries should be sent to
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Transactions
American Geophysical Union

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Eighteenth Award of the William Bowie Medal

Citation

WALTER D. LAMBERT

Mr. President, Ladies, and Gentlemen: This occasion is for me an exceptionally happy one. The Bowie Medal was established in honor of my former chief, William Bowie, whom I think of also as a good friend. And tonight we honor with the Bowie Medal a friend of mine of long standing, nearly 30 years of personal acquaintance and a still longer period of friendly correspondence.

The majority of the 17 previous medalists were citizens of this country, but only a majority, not all of them. If one were to meet tonight's medalist casually, he would think that our medalist had become a pretty good American, but the record shows that he is an intensely patriotic Finlander, citizen of a country that has been able to survive as an independent nation only because of the intense patriotism of its citizens. He is likewise a citizen of the world.

We might facetiously describe our medalist as a man who has led a double life. In fact, one of his university colleagues in this country, seeing his name on a Finnish publication in his honor, but inflected according to the intricate Finnish system, accused our medalist of changing his name when he changed his abode. But quite seriously and in a good sense he has led a double life, perhaps a multiple one. He is a citizen of Finland and Director of the Finnish Geodetic Institute, necessarily for the time being *in absentia*. He is also Director of the Institute of Geodesy, Photogrammetry, and Cartography at Ohio State University and Professor there. He has been a soldier in the army of his native country and a member of its parliament. Perhaps we could do with a few intellectuals in our own Congress. He is a man of science and also a go-getter, a rare combination

WEIKKO ALEKSANTERI HEISKANEN
Recipient, Eighteenth Award,
William Bowie Medal, May 1, 1956

His scientific interests have ranged from the heavens above to the earth beneath and to the strata many kilometers below the surface, for like Bowie, he is a student and exponent of isostasy.

One of our medalist's early achievements was the translation into Finnish of Engelmann's revision of Simon Newcomb's *Popular Astronomy*. This appeals especially to me, for in my own youth I read and admired Newcomb's book and now own a copy of Engelmann's revision and German translation. More recently our medalist returned to his early love, astronomy, by publishing a two-volume treatise setting forth in popular form the latest developments in astronomy and astrophysics. But now he has come down to earth and is best known for his work in geodesy.

One of the accepted qualifications for a Bowie medalist is cooperation in spirit and in deed. Our medalist meets this test. The Finnish Geodetic Institute is a small organization of devoted scientists, and an uncooperative director would not be likely to last very long. As to the cooperative spirit of our medalist in other ways I can testify from observation and experience. The list of his honors, his memberships in academies, his awards, his decorations, is long, too long for me to rehearse. You can read it for yourselves in the abbreviated form of the new edition of *American Men of Science*. I merely assert, Mr. President, that Weikko Aleksanteri Heiskanen of Finland, of the United States of America, and of the world is fully worthy of the medal that you are about to confer upon him.

Presentation

PRESIDENT MAURICE EWING

It is a great privilege to hand you this Medal, the Eighteenth William Bowie Medal. It represents the highest award which the American Geophysical Union can grant, and admits you to the distinguished company of William Bowie Medalists.

Response and Acceptance

WEIKKO A. HEISKANEN

Mr. President, Ladies, and Gentlemen: It is indeed for me a great pleasure and a great honor to receive the highest award of the famous American Geophysical Union. I am glad for several reasons. First, because the citation was given by Walter D. Lambert, grand old man of American geodesy, and my friend since 1923. When in my green youth I asked advice for my dissertation he sent me long informative letters. Later on the friendship has become more intimate through correspondence and personal contacts at the International Congresses, and during the last five years through the world-wide gravity program at Columbus, Ohio. Second, I am very glad that the Medal was presented by Dr. Maurice Ewing, the outstanding scholar and tireless geophysical explorer, whose enthusiasm and scientific talents I admire immensely.

But still more, I am pleased to get *the William Bowie Medal*. Three decades ago, when I started my scientific career, Dr. Bowie was the world's leading geodesist and was studying isostasy, the particular branch of geodesy that became my special scientific concern. Although he was busy with his own scientific work and with his duties as President of the International Association of Geodesy and of the International Union of Geodesy and Geophysics, he found the time to advise me about my studies. He often gave me encouragement. He also published reports in America on my first isostatic studies. He suggested that I be made his successor as the general reporter on isostasy to the International Association of Geodesy. At his and Dr. Vening Meinesz' suggestion, the International Isostatic Institute was established in Helsinki.

I think of Dr. Bowie as my scientific father. He was a scientist of highest rank, a talented international organizer, and a man of fine character. If my thanks come to the attention of his wife or son or some of his other relatives I shall be very glad indeed.

I have had more good fortune in my life than I deserve. I began as an astronomer. Astronomically, I even found my wife. My brother-in-law Y. Vaisala is an astronomer. He invited me to come to his home early on November 26, 1921 to look through his homemade telescope at the planet Mercury, which can be seen only relatively seldom. I came and saw Mercury but I saw the same morning, also for the first time, Venus, his sister-in-law, and after five months we were married.

After obtaining such good treasures in the field

of astronomy I thought what good geodesy might be able to give me and switched over to geodesy and became a geodesist of the Finnish Geodetic Institute. Professor Bonsdorff, Director of the Institute, suggested that I study the problem of isostasy. Since that time I have been faithful to this relatively new branch of geodesy. Like Bowie and several other isostasists, I realized that isostatic equilibrium prevails in broad lines all over the world. With my students I determined the thickness of the Earth's crust as shown by the gravity anomalies. It was interesting to find that the data from various different parts of the world gave for the normal thickness of the Earth's crust nearly same values, not far from 30 kilometers, also obtained seismologically.

In 1932 it was obvious to me that existing gravity material was sufficient for gravimetrical determination not only of the flattening of the reference ellipsoid but also of the shape of the geoid. Two of my co-workers published the first gravimetrically computed geoids in 1934 and 1948.

It was easy to realize that to get higher accuracy in the gravimetric study of the geoid, much more material was needed. It was also obvious after World War II that only the United States of America was interested in a gravity survey on a world-wide scale, not only on the continents but on the oceans as well. Therefore, in 1950 I was indeed very happy to be invited by Professor G. P. Harding to Ohio State University to continue the gravimetrical studies of the shape of the earth. Since that time I have paid attention mostly to the gravimetric methods or physical geodesy; not however forgetting the geophysics.

Through the intimate cooperation, not only with American institutes, universities, and oil companies, but organizations abroad as well, it seems that very soon it will be possible to solve the most important problems of geodesy. These problems are: determination of the dimensions of the reference ellipsoid, the detailed shape of the geoid, and conversion of the existing geodetic systems to the World geodetic system.

As a young Ph.D. candidate I realized how fundamentally important it is for a young scientist to get advice and encouragement from the well-known scientists. When the inspiration and the encouragement come at the right time, it may be decisive for the future of a young prospective scientist. The best that a scientist can do is to find problems for his best students and encourage and advise them. Scientists come and go, but the science continues.

Earth sciences have developed very fast in America during the last decades. Today American Earth sciences enjoy having a long list of well-known scientists of the young generation. I will mention only Drs. Maurice Ewing, Harry Hess, George Woollard, and Lamar Worzel, because they have forwarded the gravimetric method very much.

I express my deep gratitude to the President and the Executive Committee of the American Geophysical Union for their generosity to give me the knighthood in the "William Bowie Order." I promise to try to do my very best to forward the sciences of geodesy and geophysics—if God from whom all blessings flow will continue to give me health and years.

An Improved Instrument for Measurement of Tidal Variations in Gravity

H. N. Clarkson and L. J. B. LaCoste

Abstract—A self-reading continuous recording instrument for measuring changes in gravity as small as one microgal has been developed and employed in earth-tide studies. The basic force-measuring device is a modified LaCoste-Romberg gravity meter, altered to give the required accuracy. A servo-loop was designed to follow the change continuously and measurements of the tidal variation in gravity have been recorded for over two years with this instrument.

Introduction—Numerous studies of the tidal variation in gravity [*Lockenvitz*, 1944; *Reford*, 1951; *Wolf*, 1940; *Pettit*, *Slichter* and *LaCoste*, 1953] based on measurements obtained with gravity meters of the type used in oil exploration indicated the need for an instrument capable of measuring changes in gravity of less than one microgal if information concerning 'earth tides' was to be obtained.

This tidal-measuring device employs a modified LaCoste-Romberg gravity meter with the necessary provisions for making continuous measurements at least ten times as accurate as regular gravity meters. The LaCoste-Romberg gravity meter employs a 'zero' length spring as described by *LaCoste* [1934, 1935]. The measuring system is a double lever controlled by a measuring screw so designed in the normal meter that one revolution of the screw corresponds to five milligals. Figure 1 is a schematic representation of the measuring system. This meter has proven to be very reliable in oil exploration, with an accuracy approaching 0.01 milligal (ten microgals).

The gravity meter—In constructing the meter for tidal variations the amplification of the measuring system was increased by a factor of 16; thus one revolution of the measuring screw corresponds approximately to 0.3 milligal. This allowed more accurate calibration of the measuring system itself. The first readings taken with the system indicated a small non-linearity arising from the thrust (between the inner box and the top of the heater box) by the measuring screw. The magnitude of this error is too small to affect the calibration of the regular meter when employed in oil exploration, but would enter into the results obtained in tidal measurements made with such meters. This thrust was removed by replacing the section of the measuring screw that passes through the top of the heater box with a gear and pinion. The linearity of this system was better than one microgal.

For the type of measurements desired in tidal work, the system should be self-recording. Since the LaCoste-Romberg meter is a null-reading instrument, a servomechanism and selsyn were employed to operate as a continuous follow-up, self-recording system.

Following the general procedure of the construction of a gravity meter, with the exception of the above-mentioned change in lever system, the gravity meter was constructed and tested for barometric and temperature errors. Regular meters are compensated for barometric pressure changes to better than 0.02 milligal for a ten millimeter change in barometric pressure. Temperature of

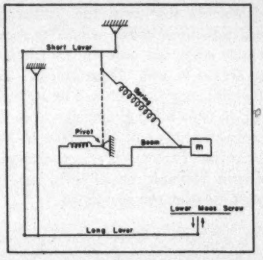

Fig. 1 – Schematic diagram of the measuring system of the LaCoste-Romberg gravity meter

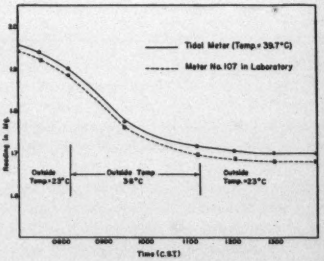

Fig. 2 – Heat drift test on the tidal gravity meter

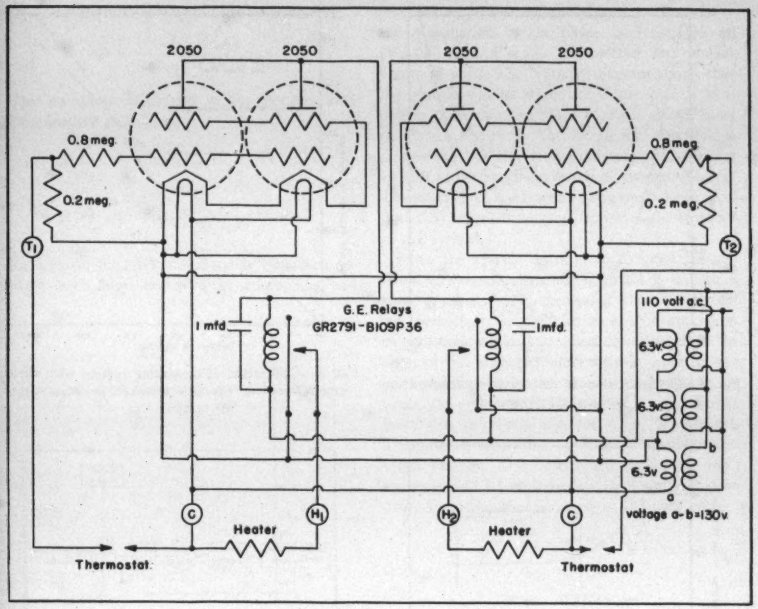

FIG 3. – Heater control circuit for tidal gravity meter

the heater box is held constant to within approximately 0.01° C and the meters must stand changes in outside temperature of at least 15°C without giving an error greater than 0.05 milligal. Obviously these requirements were not strenuous enough for the tidal meter. By using a sealed heater dox, errors that might arise due to changes in barometric pressure alone were removed from the system. A more sensitive thermostat was employed to hold the temperature of the heater box constant to within approximately 0.001°C. The effect due to changes in outside temperature was also controlled by the sealing of the inner heater box, which reduced the effect below the limit of detection under the normal test, as shown in Figure 2. As an added precaution an outside heater box was added to maintain the ambient temperature of the meter to within a few tenths of a degree Centigrade. The control circuit for both heaters is shown in Figure 3. The operating temperature of the meter is set at 39.7°C as shown by Figure 4.

This meter was tested and calibrated over a known gravity difference before the automatic reading and recording system was added. The most linear part of the measuring screw was chosen for operation of the meter. The calibration curves are given in Figure 5, indicating the part of the range in which the meter is allowed to operate. The calibration of the original measuring screw is given in Figure 6. The corrected system gave a flat response to less than one microgal.

Control system—The automatic control system (Fig. 7 shows a schematic diagram) used on the tidal meter is a speed proportional servo-mechanism. The servo-loop consists of (1) an amplifier (gain G) (2) a d c motor and the necessary gear train (inertia J, viscous damping f, motor gain constant K_1, and gear gain constant K_2) and (3) a mechanical oscillator (mass m, stiffness constant k and damping factor c). The input to this system is θ_i, the output θ_o, the difference signal ϵ, and the output of the motor θ'. The equations of motion for each system are

$$\epsilon = \theta_i - \theta_o \tag{1}$$

$$J\ddot{\theta}' + f\dot{\theta}' = K_1K_2G\,\epsilon \tag{2}$$

$$m\ddot{\theta}_o + c\dot{\theta}_o + k\theta_o = k'\theta' \tag{3}$$

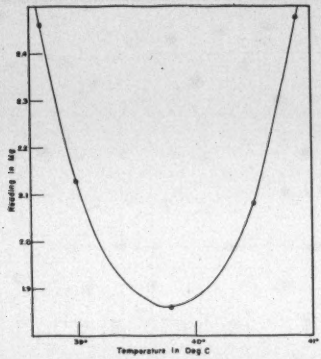

FIG. 4 – Determination of the operating temperature of the tidal gravity meter

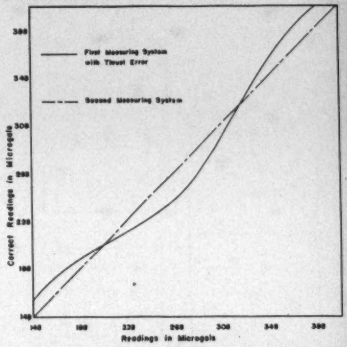
First Measuring System with Thrust Error
Second Measuring System
Correct Readings in Microgals
Readings in Microgals

FIG. 6—Calibration of measuring system with thrust error (this error was corrected in second measuring screw)

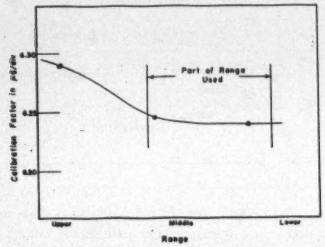

FIG. 5 – Calibration of the tidal gravity meter

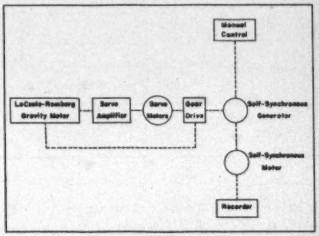

FIG. 7 – Self-reading LaCoste-Romberg tidal gravity meter employing a proportional servomechanism

In a system such as the one used in earth-tide studies, the contribution of $J\ddot{\theta}'$ in (2) is very small compared to $f\dot{\theta}'$ at the frequencies where stability is important and was neglected in consideration of this servomechanism. Thus

$$\theta' \doteq \frac{K_1K_2G}{f}\int \epsilon\, dt$$

giving as the transfer functions for the elements

$$Y_1(j\omega) = G$$

$$Y_2(j\omega) = \frac{K}{j\omega} \quad K = \frac{K_1KG}{f}$$

$$Y_3(j\omega) = \frac{\omega_0^2}{(j\omega)^2 + 2rj\omega + \omega_0^2} \quad 2r = \frac{c}{m} \quad \omega_0^2 = \frac{k}{m}$$

In order to insure additional stability a lead network was employed in the servo-amplifier. This is an RC network placed between the first and second stages of the servo amplifier. A condenser C and resistance R in parallel connect the output of stage one to the grid of stage two. The grid resistor of the second stage is R_2. The transfer function will be

$$Y_4(j\omega) = \frac{j\omega\tau + 1}{j\omega\tau + \alpha}$$

$$\tau = RC$$

$$\alpha = \frac{R + R_2}{R_2}$$

Therefore the transfer function for the servo-loop will be

$$Y(j\omega) = \frac{K\omega_0^2}{j\omega\dfrac{j\tau\omega + \alpha}{j\tau\omega + 1}(\omega_0^2 - \omega^2 + 2jr\omega)}$$

whereas for the system without the lead network

$$Y'(j\omega) = \frac{K\omega_0^2}{j\omega\,(\omega_0^2 - \omega^2 + 2j\tau\omega)}$$

The constants employed in the system were approximately as follows

$$\tau \doteq \frac{1}{\omega_0} \qquad r \doteq \omega_0$$

$$\alpha \doteq 10 \qquad \omega_0 \doteq \frac{\pi}{10} \text{ per second}$$

In Figures 8 and 9 the transfer functions are plotted both from the Nyquist standpoint and

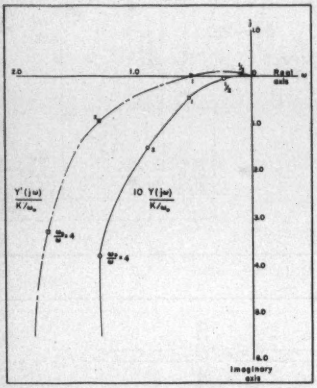

FIG. 8 - Nyquist diagram of servomechanism for the tidal gravity meter

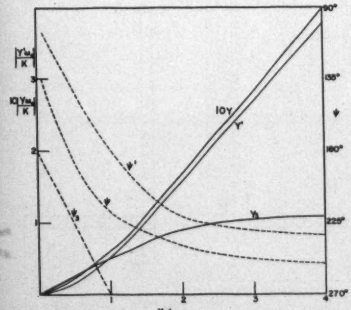

FIG. 9—Transfer functions of the servomechanism for the tidal gravity meter

from the amplitude and phase concept. Because of the attenuation in the phase lead network 10 ($Y\omega_0/K$) and $Y'\omega_0/K$ are plotted for various values of ω_0/ω. The Nyquist diagram shows that the system will be stable for either case if K is chosen properly. The effect of Y_4 is shown most clearly in Figure 9. The frequency at which ψ crosses the 180° line is approximately three times as high as the frequency where ψ' crosses this line. The response of the system, being much lower (less than 0.5) at this frequency, improves the stability of the system.

Since the system operates as a speed proportional servomechanism, the constant K will be a speed number, that is, the rate at which the system will correct for a given error ϵ. The maximum change the system is required to follow is of the order of two microgals/min; thus, in order for the error of follow to be less than one microgal at all times, the system must respond with a speed of at least two microgals/min for $\epsilon = 1$ microgal. Therefore, a lower limit on K is 0.33 per sec. The upper limit on K is determined from $\psi = 180°$; the value of $|Y|$ must be less than unity at $\psi = 180°$. At a value of $\omega = 3\omega_0, \psi = 180°$; therefore

$$Y\omega_0/K|_{\psi = 180°} = -0.02$$

thus

$$Y = -0.2K/\pi \text{ sec}$$

giving as an upper limit on K

$$K < \pi/0.2 \text{ per sec}$$

This can be compared with the value obtained from

Y' at $\psi = 180°$, $\omega = \omega_0$

$$Y'\omega_0/K|_{\psi' = 180°} = 0.5$$

therefore

$$Y' = 5K/\pi \text{ sec}$$

$$K < \pi/5 \text{ per sec}$$

It follows from this that a great deal more range in K is obtained by use of the lead network. The approximate value of K for the system was two per second.

The servo-amplifier, including the lead network is shown in Figure 10. The system is fundamentally a balanced d c current amplifier, which operates on a difference in potential between the grids of the 5693's. This potential difference is produced by a difference in illumination on the comparison photocells. Figure 11 is a sketch of the meter with the photoelectric reading system employed in the

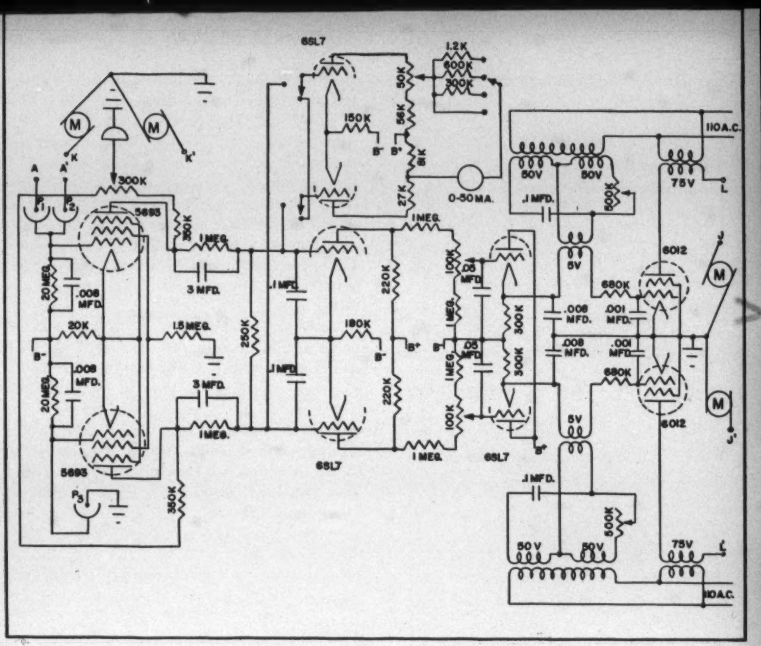

FIG. 10 – Servo-amplifier for tidal gravity meter

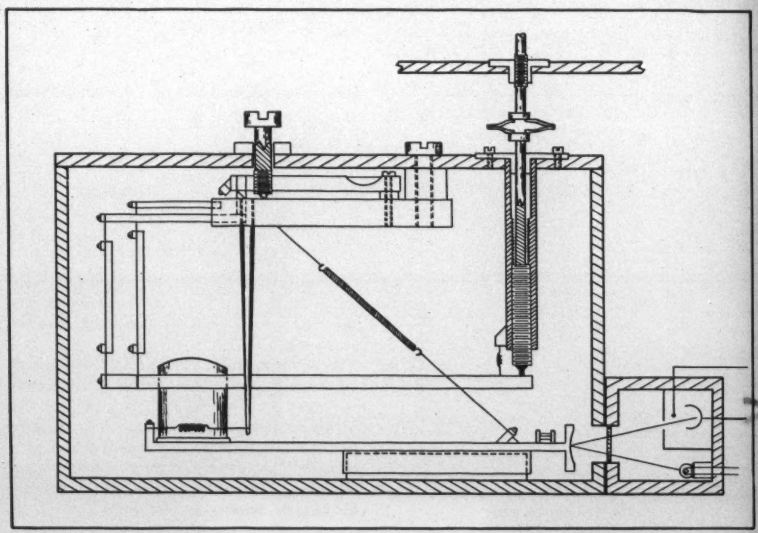

FIG. 11 – LaCoste-Romberg gravity meter with photoelectric reading system

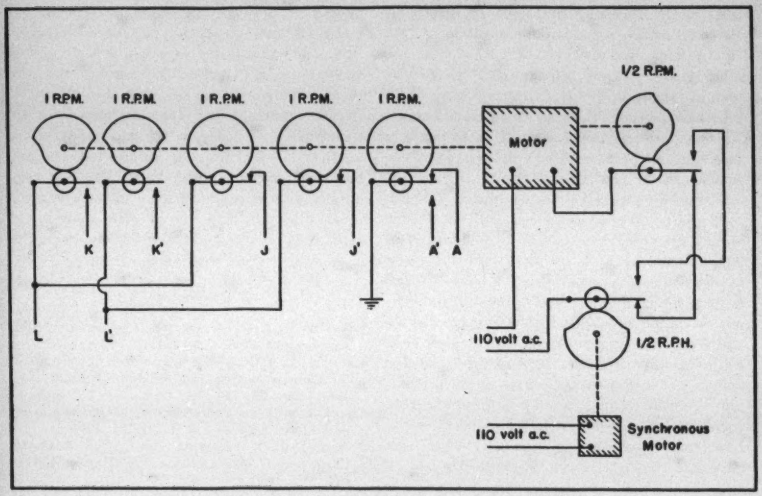

FIG. 12 – Automatic zero adjust for servo-amplifier

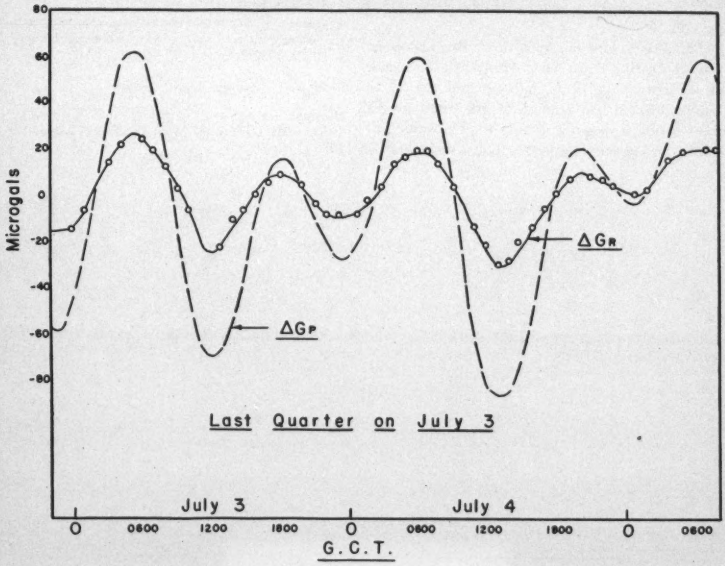

FIG. 13 – Predicted tidal variation in gravity and "Earth tide," July 3–July 4, 1953, Austin, Texas

tidal meter. Referring to Figure 10, photocells P_2 and P_3 have a constant illumination so that (under these conditions) a zero for the system is established. In Figure 10 photocell P_1 receives its illumination by an optical path including a concave mirror on the end of the beam of the gravity meter. This light passes through a small slit so that any motion of the beam results in a change in this illumination. A clock-driven device (Figure 12) automatically switches from the meter photocell to the standard photocell once each hour, for one minute's duration, to establish the amplifier zero. This also switches from the servo motors to a pair of identical motors, which drives a helipot placed in the plate circuit of the 5693's. Any drift throughout the entire d c system is thus compensated for and a constant amplifier zero is maintained. Grid controlled thyratrons are used to drive the d c motors which turn the measuring screw to maintain the null reading. A take-off from the gear train drives a selsyn system which operates the Leeds and Northrop pen recorder, which was altered to allow the selsyn to operate the pen. A differential placed in the selsyn drive provides a method of changing the reference on the recorder to allow for any drift in the gravity meter. The drift of the meter is approximately 30 microgals per month.

This tidal meter has been in continuous operation in Austin, Texas since April, 1953 and some of the data have been analyzed and the 'earth tide' calculated. An example of the result over a short period is shown in Figure 13. The value calculated by considering the Earth as a rigid body is labeled by ΔG_t and the difference between the measured value and the calculated value by ΔG_R. The Institute of Geophysics at University of California at Los Angeles has been furnished with the data obtained from this instrument. Utilizing the data obtained from the tidal meter, the Institute plans to make an extensive study of the 'earth tide.' In the near future LaCoste and Romberg plans to furnish the Institute of Geophysics with an improved tidal meter which will be more portable and a world wide study of the earth tides will be undertaken. A report on this instrument will be forthcoming.

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Note on the Components of Magnetic Intensity at Inverse Points Relative to a Spherical Boundary

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Abstract—Equations are derived which govern the relation between the values of a field component at points that are inverse relative to a spherical boundary carrying the distribution of sources. Inversions are made for surface and double layer distributions. The existence of simple relations of this character accompanies the existence of continuity of the component at the boundary.

It is a well-known fact that a function harmonic and regular inside and outside a spherical surface can be represented as the sum of potentials due to either a surface distribution or a double layer on the surface. It is also well known that at points that are inverse with regard to the sphere, there is a simple relationship between the potentials due to a surface distribution. It is the purpose here to discuss similar relations for the components of the intensity arising from both types of distribution. Though developed in relation to magnetic fields (for example, those arising from ionospheric currents), the results are also applicable to electrostatic and gravitational fields. The general expressions used for the potential and its normal derivative are those treated by *Chapman* and *Bartels* [1940]. Throughout this note, the subscript o refers to points outside a sphere of radius $r = a$ on which the sources are distributed: the subscript i, to points inside.

The potentials outside and inside a spherical surface with a surface density f may be written respectively as

$$V_o = a \sum_{n=0}^{\infty} \frac{4\pi}{2n+1} \left(\frac{a}{r_o}\right)^{n+1} S_n(\theta, \phi) \qquad (1)$$

and

$$V_i = a \sum_{n=0}^{\infty} \frac{4\pi}{2n+1} \left(\frac{r_i}{a}\right)^{n} S_n(\theta, \phi) \qquad (2)$$

where $S_n(\theta, \phi)$ is a spherical surface harmonic of degree n, θ the colatitude, ϕ the east longitude, and

$$f = \sum_{n=0}^{\infty} S_n(\theta, \phi) \qquad (3)$$

Let the sphere $r = a$ be centered at the origin O, and consider two points P_o and P_i lying on a common radius, with $r_o r_i = a^2$, where $r_o = OP_o$ and $r_i = OP_i$. Such points are said to be inverse with regard to the sphere. If we substitute from this relation into (1) or (2), the right-hand members of (1) and (2) become alike except for the exponent; hence, we have for inverse points

$$\frac{V_o}{V_i} = \frac{a}{r_o} = \frac{r_i}{a} \qquad (4)$$

Thus, from the potential at one of the inverse points it is possible to determine rigorously the potential at the other point. We resort to (1) and (2) again to bring out a similar characteristic for the northern and eastern components of magnetic intensity, using respectively,

$$X = \frac{1}{r} \frac{\partial V}{\partial \theta} \qquad (5)$$

and

$$Y = -\frac{1}{r \sin \theta} \frac{\partial V}{\partial \phi}$$

By substitutions identical with those applied to the potential, one obtains at inverse points

$$\frac{X_o}{X_i} = \left(\frac{r_i}{a}\right)^3 = \left(\frac{a}{r_o}\right)^3 \qquad (6)$$

and

$$\frac{Y_o}{Y_i} = \left(\frac{r_i}{a}\right)^3 = \left(\frac{a}{r_o}\right)^3 \qquad (7)$$

No simple equality such as (4), (6), or (7) exists for the downward component Z, given by $\partial V/\partial r$, for a surface distribution.

With a distribution of dipoles, or double layer, on a spherical shell, the potentials may be written as

$$V_o = 4\pi \sum_{n=0}^{\infty} \frac{n}{2n+1} \left(\frac{a}{r_o}\right)^{n+1} M_n(\theta, \phi) \qquad (8)$$

and

$$V_i = -4\pi \sum_{n=0}^{\infty} \frac{n+1}{2n+1} \left(\frac{r_i}{a}\right)^{n} M_n(\theta, \phi) \qquad (9)$$

where the dipole moment per unit area is

$$M = \sum_{n=0}^{\infty} M_n(\theta, \phi) \qquad (10)$$

The Z component for points not on the shell is given by

$$Z_o = -4\pi \sum_{n=0}^{\infty} \frac{n(n+1)\, a^{n+1}}{(2n+1)\, r_o^{n+2}} M_n(\theta, \phi) \quad (11)$$

and

$$Z_i = -4\pi \sum_{n=0}^{\infty} \frac{n(n+1)\, r_i^{n-1}}{(2n+1)\, a^n} M_n(\theta, \phi) \quad (12)$$

For inverse points one obtains

$$\frac{Z_o}{Z_i} = \left(\frac{r_i}{a}\right)^3 = \left(\frac{a}{r_o}\right)^3 \quad (13)$$

as the relationship for the normal component of the double distribution. No simple relation such as (13) exists for V, X, or Y for the dipole distribution.

Thus, depending on the type of distribution, inversions in the sphere can be made for different elements. The validity of the inversion leading to the simple equality is directly related to the continuity of the element at the boundary carrying the distribution. If the element is continuous, the inversion can be made and the simple relation exists. For example, at the surface with a double layer, Z is continuous, and (13) can be derived, but V, X, and Y have discontinuities of $4\pi M$, $4\pi \partial M/a\partial\theta$, and $4\pi \partial M/a \sin\theta \partial\phi$, respectively. Conversely, at the surface distribution, V, X, and Y are continuous but Z has a discontinuity of $4\pi f$.

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Note on the Effect of Air-Sea Temperature Difference on Wave Generation*

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Abstract—Observations from certain ocean weather ships are used to determine whether or not a certain observed wind speed in cold air (relative to sea temperature) leads to higher waves than does the same wind in warm air. The problem is to eliminate possible correlation between fetch and air-sea temperature difference. It is concluded that significantly higher waves are generated in cold air than in warm air, the difference amounting to roughly ten per cent of the warm air values per degree Centigrade.

Introduction—The question of whether or not for the same measured wind speed sea surface waves develop more rapidly and reach greater heights in cold air than in warm air appears not to have been settled. On the one hand, the relation between air-sea temperature difference and wave generation is supported by references in the literature [for example, *Munk*, 1947; *Brown*, 1953], and it is widely believed in by sailors and ship captains. A recent paper by *Darbyshire* and *Darbyshire* [1955] shows that the surface stress as measured by tilt of the surface of a lake is greater for cold air than for warm air; however, no conclusion with respect to wave generation was made. On the other hand, *U. S. Hydrographic Office* [1951] does not recognize the effect as it might apply to observed winds, nor does most oceanographic literature concerned with wave generation. It is quite reasonable that the judgment of seamen concerning the effect of the air-sea temperature difference might reflect only a correlation between air temperature and wind speed or fetch, so that subjective judgments must be viewed with skepticism.

The relation of air-sea temperature difference to the ratio of geostrophic to measured wind has been widely recognized and has been incorporated into present wave forecasting methods. The subject of this paper is the further relation of air-sea temperature difference to the ratio of measured wind to wave generation (roughly, surface stress). It would be possible to determine, instead, the relation of air-sea temperature difference to the ratio of geostrophic wind to wave generation, but this would duplicate in part earlier studies and would not directly answer the question stated above.

A statistical study of the relation has been made by *Roll* [1952], who has found that for the same wind speed, as measured at certain North Atlantic weather ships, the mean wave height when the water temperature is 6.7°C above the air temperature is 22 pct greater than when air and sea temperatures are equal. Roll has discussed the observations and their statistical significance at some length, so that there is no reason to doubt that these results can be duplicated qualitatively by the same test performed on other data. However, Roll did not consider the possibility that the statistical relation between air-sea temperature difference and wave height might reflect a correlation between temperature difference and fetch rather than a physical relation between aerostatic stability and wave generation. The study presented here has been undertaken to determine the relationship between air-sea temperature difference and wave height, if any, under conditions of constant fetch.

Method—Daily weather-ship data tabulated in the Daily Series Synoptic Weather Maps [*U. S. Weather Bureau*, 1949–1953] for the periods August–September 1950, and January 1952–February 1953 inclusive have been used in the study. Observations from the Atlantic station vessel HOTEL at approximately 36°N, 70°W (approximately 270 mi east of the U. S. coastline) and the Pacific station vessel SIERRA at approximately 48°N, 162°E (approximately 300 mi southeast of Kamchatka) have been used. These ships experience a wide range of air-sea temperature difference, and the fetch during periods of extreme temperatures is determined mostly by the distance of the ships from land. Cases were selected from analyzed sea-level charts in which streamlines were essentially straight and were directed from land to the ship.

The following criteria were used in selecting cases. For each case at the Atlantic ship the reported wind direction lay between 240° and 360°, and for each case at the Pacific ship the reported wind direction lay between 260° and 330°. The streamlines were essentially straight both upwind and downwind for about 300 mi from the ship. These two criteria together provide reasonable assurance of a fetch approximately equal to the

* Contribution No. 20, Department of Meteorology and Climatology, University of Washington.

distance of the ship from the shore. In all cases selected wind and wave directions were within 20° of each other, and cases of confused seas were excluded.

Wind speed, wave height, and air temperatures were taken directly from the tabulated data. Sea surface temperatures were taken from the tabulated data where available and, otherwise, from smoothed curves of the annual sea surface temperature obtained from *U. S. Weather Bureau* [1938]. More elaborate methods involving the temperature of the air prior to moving over land were tried without noticeable effect on the relationship under study.

The method described above offers no assurance that in the cases selected the waves had reached their maximum height for the fetch used. The available data do not permit an accurate estimate of the duration of the wind, but it is possible to select cases with reasonable accuracy in which the wind velocity had remained essentially unchanged during more than 24 hr. This additional criterion was used without noticeable effect on the relationship between air-sea temperature difference and wave height; therefore this criterion was abandoned.

It was finally concluded that the criteria described above afford unbiased data and that they provide resolution of the air-sea temperature difference effect which is as accurate as the basic data permit.

Results—The variance of the individual observations is so great that any possible relationship between temperature and wave height is bound to be obscured by scatter. However, if the individual cases are grouped according to arbitrary ranges of air-sea temperature difference and if these data are then sub-grouped according to wind speed, meaningful averages can be obtained. These averages for groups of ten cases are shown in Figures 1 and 2.

Figure 1 shows, that for the same wind speed, higher waves are generated in cold air than in warm air. This is particularly marked at low and high wind speeds and is less marked at intermediate speeds, but no certain significance can be attached to this secondary relation because of the rather small number of cases (ten) used in computing each of the plotted points. Figure 1 shows, as a rough generalization, that by itself the effect of change of air-sea temperature difference from −2.5°C to 8.5°C is to double the wave height. Or, in different terms, change from −2.5°C to 8.5°C keeping wave height constant is equivalent to halving of the wind speed. Figure 2 shows a

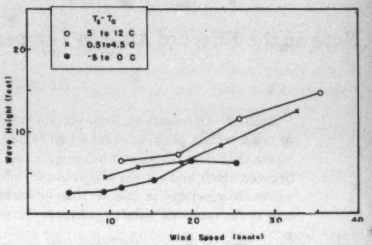

FIG. 1 – Relationship between air-sea temperature difference and wave height for 150 cases observed at HOTEL at 36°N, 70°W; each point represents an average wave height and wind speed for ten cases

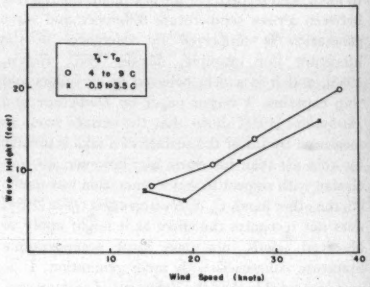

FIG. 2 – Relationship between air-sea temperature difference and wave height for 77 cases observed at SIERRA at 48°N, 162°E; each point represents an average wave height and wind speed for ten cases

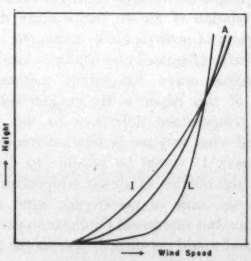

FIG. 3 – Characteristic wind velocity profiles under conditions of inversion I, adiabatic lapse rate A, lapse L

qualitatively similar result; the magnitude of the effect is smaller, corresponding to the smaller range of air-sea temperature difference. The evidence of both figures indicates that wave height

increased with sea-air temperature difference at roughly ten per cent per degree Centigrade. These results are convincing evidence that higher waves are generated by cold air over warm water than by warm air over cold water. For extremes of air-sea temperature difference the effect is large and, therefore, of considerable practical importance.

Explanation—Unfortunately, although there is general agreement among meteorologists that the vertical flux of momentum in the atmosphere depends upon the vertical temperature gradient as well as upon the vertical shear, the wind speed, and the nature of the surface, there exists no recognized theory which includes this relation. Of course, it is this lack of a comprehensive theory which accounts for the fact that the relation between vertical temperature gradient and wave generation has not been universally recognized. Therefore, in what follows only qualitative, largely intuitive, explanations are given.

The stress in the atmosphere is almost entirely a turbulent stress known as a Reynolds' stress and is expressed by

$$\tau/\rho = \overline{-u'w'} \qquad (1)$$

where τ represents stress; ρ, density; u' and w', eddy velocity components in the horizontal and vertical directions, respectively; the bar indicates the operation of averaging. Eq. (1) describes the tangential stress in the air above the water surface, but it is very closely equal to the stress at the surface. It is well known that buoyant force in aerostatically unstable air (lapse conditions) leads to rapid vertical displacements accompanied by gusts, whereas the buoyant force in aerostatically stable air (inversion) leads to smooth flow without strong gusts. Because the vertical and horizontal gusts are highly correlated (negatively) it is clear from (1) that the stresses in the two cases may be substantially different. Compared to this effect, the higher density of cold air as opposed to warm air exerts only a very small effect.

An alternate, but not independent, explanation depends upon detailed knowledge of the mean wind speed profile near the water. Careful measurements over a water surface by *Hay* [1955] and unpublished measurements made by the writer and his associates show that in inversions the wind speed near the surface increases less rapidly with height than it does under conditions of adiabatic stratification or in lapse conditions. This is consistent with conclusions drawn by *Deacon* [1949] for wind profiles over smooth land surfaces, although the quantitative agreement of the over-water observations with Deacon's equation is very poor. This lack of agreement no doubt reflects the finite size of eddies determined by the surface waves. In any event, the greater vertical shear in lapse as opposed to inversion conditions (Fig. 3) indicates greater stress at the water surface. This relation between stress and vertical shear may be expressed explicitly by Deacon's equation. The fact that the wind over water does not fit Deacon's equation means that Deacon's equation cannot be used quantitatively in this case, but it surely must be supposed that the qualitative significance is maintained. And, indeed, observations by *Darbyshire* and *Darbyshire* [1955], cited earlier, show the stress as determined from slope of the surface to be greater under lapse than inversion conditions.

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Observations of Internal Tides in October 1950*

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Abstract—Over six days of anchor station hydrographic data from each of three vessels on a line 280 mi long were analyzed for internal waves of tidal (and other) periods. Waves of semidiurnal period with amplitudes greater than 30 ft were found at the nearshore station (40 mi offshore in 1080 fm), but little evidence of these waves or any other periodic phenomena was found at the stations farther offshore though there was considerable vertical fluctuation of isotherms. It is suggested that the waves found originate near the coast in the action of the surface tides and that, since the length of such waves, if free, is short, they either dissipate before proceeding far offshore or, more likely, are so distorted by the varying density structure and water velocity that they are no longer recognized.

Introduction—The effect of internal waves of tidal period upon the interpretation of dynamic topography has concerned various authors, among them *Seiwell* [1939] and *Defant* [1950ab]. *Rudnick* and *Cochrane* [1951] have examined three long series of data from points far from shore and found but little evidence of tidal periods. *Haurwitz* [1954] has demonstrated that short series (24 to 72 hr) can hardly yield conclusive results since the amplitudes may be the result of random fluctuations. *Rudnick* and *Cochrane* [1951] suggest that some limitation exists as to place and manner of occurrence of internal tidal waves, and that they may be generated at ocean boundaries. *Arthur* [1954] has examined temperature data from two piers and from an area within four kilometers of one of them, and found oscillations which suggest the possibility of tidal periodicities, though not as regular as the surface tides, and which would be consistent with an internal wave mechanism. *Haurwitz* [1950] has shown that internal tidal waves may have lengths of the order of 20 to 40 mi. *Rattray* [1954] has considered the effect of eddy viscosity upon such waves and concluded that their amplitude would be reduced by one-half at distances of from 120 to 15,000 km, depending mostly upon eddy viscosity, depth of the shallower layer (in a two-layer system), and the density difference.

Observations discussed in this paper bear upon the place of origin and subsequent behavior of certain internal tidal waves.

Observations of internal tides in October 1950—Beginning October 11, 1950, three vessels occupied positions at distances of 40, 160, and 320 nautical mi offshore on a line running 240° true from Point Sur, California, at depths of 1080, 2350, and 2415 fm respectively (Fig. 1). The nearshore vessel was anchored for seven days. The others were kept on station for eight days by celestial navigation. Hourly bathythermograph (BT) lowerings were made and hydrographic casts at intervals of three hours were taken for temperature, salinity, and oxygen determinations. Casts at Greenwich noon and midnight were made to 1000 m, others to 300 m. Wind varied over the area and period from calm to Beaufort force 6, but was mostly less than force 4.

The purpose of the cruise was to observe the internal waves, particularly those of tidal character, and to provide information for the interpretation of dynamic topography over the area.

Figures 2 and 3 show representative data from the three stations and the semidiurnal part of the predicted tide at the nearest part of the coast (with no phase adjustment but an arbitrary amplitude-scale ratio of 20/1). At the nearshore station the rise and fall of the thermocline immediately suggests semidiurnal tidal behavior. No such behavior is apparent to the eye at the outer stations. A harmonic analysis has been performed and a reality test employed for periods of 12.4206 (M_2), 12 (S_2), and 24 hr (K_1). Data used were depths of thermocline and isotherms from the

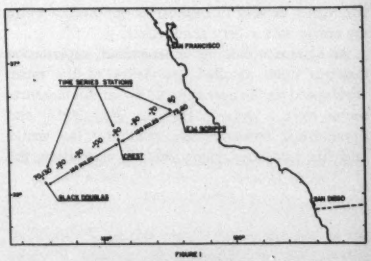

FIG. 1 – CCOFI Cruise 5011 (MLR 19), November, 1950

* Contribution from the Scripps Institution of Oceanography, New Series, No. 855.

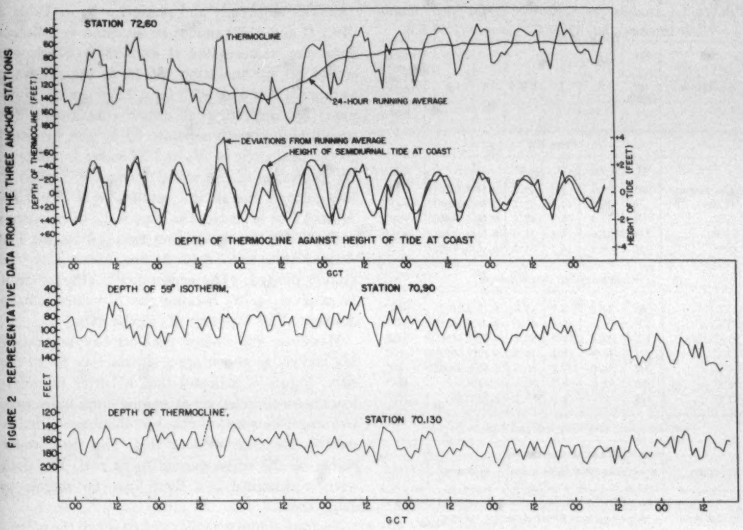

FIGURE 2 REPRESENTATIVE DATA FROM THE THREE ANCHOR STATIONS

FIG. 2 - Representative data from the three anchor stations

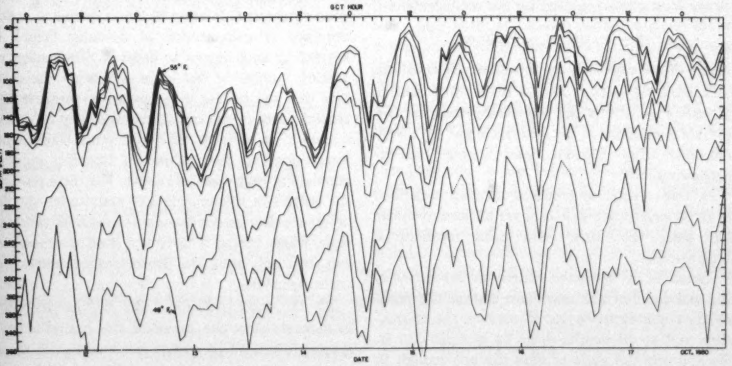

FIG. 3 - Oscillation of isotherms (from bathythermograph), station 72.60

BT depths of isotherms of the interpolated data of the reversing thermometers, and the dynamic height anomaly 0/300 db.

Method of analysis and reality test—Tables 1 to 6 give the amplitude A and also the quantities E, k^2, and p as used by *Haurwitz* [1954] in the expectancy method described by *Stumpff* [1940] and *Chapman* and *Bartels* [1940]. For derivations see the last two, and for a brief discussion of the applicability of the method to this sort of data see *Haurwitz* [1954]. Roughly, the method shows the probability that the amplitude A might have been obtained from random rather than periodic fluctuations in the data. If the data are divided

TABLE 1 – *Analysis for 12.4206-hr period (M_2), Station 72.60 (inshore), lat. 35°35.5'N, long. 122°07.5'W*

Datum	Average depth	A	E	RMS	k^2	p	Phase at 21h00m GCT Oct. 11, 1950
From BT							
	ft	ft	ft	ft			
Thermocline	101	29.4	9.1	39.2	9.54	0.000071	−10°
TCdev	0	31.8	10.1	27.7	9.86	0.000053	−11°
55°F	94	29.8	9.3	37.8	9.56	0.000068	−16°
52°F	134	33.6	9.8	37.0	9.76	0.000058	−16°
49°F	270	48.2	14.5	41.0	10.90	0.000018	3°
From reversing thermometers							
13°C	88	23.2	8.8	43.0	6.72	0.0012	−11°
12°C	104	34.8	10.4	41.6	9.03	0.00011	−14°
11°C	135	32.8	10.2	38.7	9.81	0.000055	−13°
10°C	217	40.0	12.5	44.3	9.92	0.000050	3°
9°C	332	24.0	9.2	31.1	8.68	0.000018	29°
8°C	590	22.0	10.2	30.4	4.44	0.012	118°
7°C	895	9.5	11.2	55.1	0.74	0.48	188°
From reversing thermometers and Nansen bottles							
	dyn m	dyn m	dyn m	dyn m			
ΔD 0/300	0.581	0.0070[a]	0.0029	0.010	5.89	0.0028	12°

[a] Separating M_2 and S_2 by the method of least squares described in the text this value becomes 0.0111 dynamic meters.

into n intervals of the period examined and each of the n intervals analyzed for the coefficients in

$$y = a_i \cos mt + b_i \sin mt$$

where $m = 2\pi/\text{period}$, the expectancy E is defined as $1/n\sqrt{\Sigma a_i^2 + \Sigma b_i^2}$. Then k is the ratio of A to E, and $p = e^{-k^2}$ is the probability that the amplitude A obtained in the analysis might have been obtained from random data having the expectancy E.

In the method of stepwise analysis described in the appendix the a_i and b_i are at once available for both the lunar and solar semidiurnal evaluations.

Results at the nearshore station and separation of M_2 and S_2—For the nearshore station the probability test indicates a real M_2 wave in the thermocline and at all depths down to at least 332 ft. Six and one-half days of data are not enough to separate clearly the constituents M_2 and S_2, but the amplitude from the M_2 analysis was the greater. Figure 2 shows the daily amplitude of the thermocline (TC dev, the deviation from the 24-hr running mean) to be waning with the predicted tide, with a high value somewhere near the time of new moon (13h33m GCT October 11) when M_2 and S_2 should be in phase, declining toward the first quarter (04h18m GCT October 18). The amplitude and phase for S_2 in Table 2 (19.1 ft and 276°) cannot be accepted as different from the values (19.3 ft and 258°) which one would get by analyzing 156 hr of the M_2 wave values (31.8 ft and 349°) for a 12-hr period. However, by neglecting all other constituents the amplitudes of each separate 12 hr can be fitted to the beat cycle of M_2 and S_2 waves in phase at the beginning of the series. Using the method of least squares one obtains amplitudes of 28.0 ft for M_2 and 12.3 ft for S_2. The ratio is 2.3 as compared with 2.2 for the equilibrium tide, 2.4 for the Los Angeles tide, and 3.8 for Morro, Morro Bay, the station plotted. (The expectancy method cannot be applied for S_2 because the E values will be dominated by the large M_2 in the data.)

However, the values obtained by separating M_2 and S_2 as above are a satisfactory fit to the data. Figure 4 indicates that a better fit might have been obtained by averaging amplitudes over two lengths instead of one, but the demonstration seemed adequate without this. The three worst points on the curve seemed to be real. The data were re-examined but there was no reason to doubt them.

Figure 5 shows a similar treatment of the amplitude of the dynamic height ΔD 0/300 db. There is more scatter in the points but the trend is in good agreement. It must be remembered that the accuracy of computation of dynamic height is limited by such errors as depth-determination of bottles, number of bottles available on the cast, how well the bottles were spaced to measure the critical parts of the curve, the accuracy of determination of salinity, and the final trapezoidal integration of the values of specific volume anomaly at each standard depth. For these reasons the scatter of dynamic height amplitudes should be expected to exceed those of the depth of thermocline, whose errors, if there is a good thermocline, can stem only from the depth-sensing element of the instrument.

By the same reasoning, the depths of those isotherms below the range of the bathythermograph are subject to greater error, and since these isotherms are in the region where the vertical gradients are much smaller, the values of amplitude and probability of the 9°C isotherm and below are probably less accurate than those above.

We may conclude, then, that there were present both an M_2 and an S_2 component in the thermocline and at all depths down to 332 ft and possibly deeper.

Results at the two outer stations—The outer

TABLE 2 – *Analysis for 12- and 24-hr periods, Station 72.60*

Datum	12-hr period (S_2) A	E	k^2	p	Phase at 21h00m GCT Oct. 11, 1950	24-hr period A	E	k^2	p	Phase at 21h00m GCT Oct. 11, 1950
From BT										
	ft	ft				ft	ft			
Thermocline	20.6	9.1	4.99	0.0068	−80°	4.7	3.9	1.44	0.23	15°
TCdev	19.1	10.1	4.29	0.014	−84°	...	...	...	...	...
55°F	19.1	9.3	4.67	0.0094	−84°	...	...	...	...	...
52°F	22.2	9.8	5.13	0.0059	−85°	...	...	...	...	...
49°F	32.6	14.5	6.03	0.0024	−84°	...	...	...	...	...
From reversing thermometers										
13°C	13.5	8.8	2.26	0.10	−76°	5.0	10.7	0.31	0.73	−4°
12°C	21.2	10.4	4.30	0.014	−88°	...	...	...	...	...
11°C	21.2	10.2	4.43	0.12	−85°	2.0	3.9	0.26	0.77	92°
10°C	34.3	12.5	7.77	0.00043	−69°	...	...	...	...	...
9°C	22.8	9.2	6.64	0.0013	−61°	...	...	...	...	...
8°C	13.9	10.2	1.92	0.15	27°	2.8	3.9	0.54	0.58	−40°
7°C	6.1	11.2	.32	0.73	−22°	...	...	...	...	...
From reversing thermometers and Nansen bottles										
	dyn m	dyn m				dyn m	dyn m			
ΔD 0/300	0.0058[a]	0.0029	3.98	0.019	−39°	0.0045	0.0036	1.56	0.21	−4°

[a] Separating M_2 and S_2 by the method of least squares, this value becomes 0.0065 dynamic meters.

TABLE 3 – *Analysis for 12.4206-hr period (M_2), Station 70.90 (center), lat. 34°51′N, long. 124°33′W*

Datum	Average depth	A	E	RMS	k^2	p	Phase at 21h00m GCT Oct. 11, 1950
From BT							
	ft	ft	ft	ft			
Thermocline	67	1.2	3.4	18.2	0.13	0.88	166°
59°F	101	4.2	3.8	21.5	1.22	0.30	6°
From reversing thermometers							
16°C	85	3.3	2.6	19.6	0.69	0.50	48°
12°C	117	6.0	4.5	26.1	1.77	0.16	4°
10°C	229	3.2	5.3	32.0	0.35	0.70	316°
9°C	420	4.3	7.2	29.5	0.36	0.70	226°
8.5°C	658	8.1	9.0	31.6	0.81	0.44	194°
8°C	952	1.1	7.8	35.5	1.82	0.16	250°
From reversing thermometers and Nansen bottles							
	dyn m	dyn m	dyn m	dyn m			
ΔD 0/300	0.604	0.00055	0.0025	0.009	0.04	0.96	200°

stations (Tables 3 to 6) show very little evidence of periodic behavior in any of the three tidal periods tested. A periodogram analysis was run upon the thermoclines for periods from six to 27 hr (including the period of inertial rotation) with no significant amplitudes being indicated. The root mean squares of the variation of the depth of the thermoclines at the two outer stations were somewhat less than at Station 72.60, but at lower depths they were more nearly equal, and the RMS of the variation of dynamic height above 300 db were nearly equal at all three positions. Thus the energy of fluctuation does not seem to be very much less at the outer stations, but the clearly defined waves of the inner station are not found offshore in any recognizable form.

Wave length and speed—Haurwitz [1950] has derived a theoretical expression (in which he considers the rotation of the Earth) for the relationship between the period, wave length, density structure, and depth in a two-layer system. Writing it to express L as a function of the other quantities

$$\frac{2\pi}{L} = \sqrt{\frac{(\sigma^2 - \lambda^2)\,(h' + h'')}{gh'h''\,(1 - \rho'/\rho'')}}$$

where

L = wave length
$\sigma = 2\pi/T$, T = period
$\lambda = 2\omega\sin\phi$, the Coriolis parameter
ω = Earth's rotation
ϕ = latitude

h', ρ' = the depth and density of the upper layer
h'', ρ'' = the depth and density of the lower layer

TABLE 4 – *Analysis for 12- and 24-hr periods, Station 70.90*

Datum	12-hr period (S_1) A	k²	p	Phase at 21h00m GCT Oct. 11, 1950	24-hr period A	E	k²	p	Phase at 21h00m GCT Oct. 11, 1950
				From BT					
	ft				ft	ft			
Thermocline	4.6	0.84	0.43	−43°	7.0	3.8	3.41	0.022	46°
59°F	7.8	4.27	0.014	241°	4.6	3.5	1.64	0.19	83°
				From reversing thermometers					
16°C	5.6	1.80	0.50	237°	3.5	4.2	0.69	0.50	65°
12°C	4.2	0.88	0.41	227°	6.4	5.1	1.62	0.20	90°
10°C	9.5	3.25	0.04	203°	11.3	9.6	1.44	0.25	136°
9°C	7.2	0.98	0.38	225°	8.5	7.8	1.25	0.30	227°
8.5°C	4.9	0.35	0.70	78°	5.9	9.3	0.41	0.67	299°
8°C	2.2	0.08	0.92	13°	5.4	9.9	0.34	0.74	59°
				From reversing thermometers and Nansen bottles					
	dyn m				dyn m	dyn m			
ΔD 0/300	0.0042	2.45	0.09	239°	0.0021	0.0035	0.38	0.70	208°

Using values from the nearshore station (and estimating $1 - \rho'/\rho''$ at from 0.001 to 0.003 since we do not have a two-layer system) L is from 17.3 to 42.5 mi and the velocity from 1.40 to 2.36 knots.

Rattray [1954] has considered the effect of eddy viscosity upon such waves, and has found that the length is slightly decreased. A damping coefficient is derived. Entering the data at the inner station in his expression, the amplitude is found to be reduced by one-half at a distance of from 136 to 1360 mi (taking eddy viscosity at from 1 to 100 cm²/sec). This alone would not account for the lack of coherence of the data at the first two stations, as can be seen from the amplitudes of the dynamic height variations listed in Tables 1 to 4. (When the vertical density gradients vary horizontally, as in these data, the amplitudes in feet of the depths of isotherms at two stations may not be comparable measures of wave height, and it is thought best to compare amplitudes of dynamic height.)

In any case the waves are not indicated clearly enough at the two outer stations for the velocity to be computed from phase differences. No coherence is found between stations. This is not inconsistent with the theoretical wave lengths of 20 to 40 mi. If there are several wave crests between stations (as in this case) traveling through areas of different and changing density structure and layer depth and across a moving stream, then they may be distorted and attenuated [*Rattray*, 1954] to the extent of not being recognizable.

TABLE 5 – *Analysis for 12.4206-hr period (M_2), Station 70.130 (offshore), lat. 33°33'N, long. 127°16.5'W*

Datum	Average depth	A	E	RMS	k²	p	Phase at 21h00m GCT Oct. 11, 1950
				From BT			
	ft	ft	ft	ft			
Thermocline	167	3.2	2.3	13.4	1.96	0.14	196°
60°F	180	2.1	3.6	20.9	0.31	0.74	211°
				From reversing thermometers			
17°C	175	2.7	4.3	17.1	0.43	0.64	78°
15°C	224	5.9	5.4	25.5	1.16	0.31	16°
13°C	310	2.8	6.6	29.8	0.20	0.82	296°
11°C	404	14.7	8.0	35.7	3.40	0.033	316°
10°C	470	13.4	7.9	31.0	2.82	0.060	291°
9°C	617	15.8	8.0	29.5	3.69	0.025	293°
8°C	855	6.6	7.4	37.0	0.70	0.50	−19°
				From reversing thermometers and Nansen bottles			
	dyn m	dyn m	dyn m	dyn m			
ΔD 0/300	0.813	0.0032	0.0033	0.011	0.95	0.41	278°

Tidal effects in the dynamic height—Of the three stations, at only the nearshore one were internal waves of tidal period observed. Here the semidiurnal tidal amplitudes describe the larger part of the fluctuation. The author knows of no other data in the literature which yield such striking evidence of the existence of tidal internal waves.

TABLE 6 – *Analysis for 12- and 24-hr periods, Station 70.130*

Datum	12-hr period (S_2) A	k^2	p	Phase at 21h00m GCT Oct. 11, 1950	24-hr period A	E	k^2	p	Phase at 21h00m GCT Oct. 11, 1950
From BT									
	ft				ft	ft			
Thermocline	0.7	0.09	0.91	124°	2.9	2.2	1.81	0.16	−48
60°F	2.2	0.36	0.70	44°	4.7	4.3	1.17	0.31	−79°
From reversing thermometers									
17°C	4.2	0.93	0.39	129°	5.3	3.7	2.10	0.12	72°
15°C	0.7	0.018	0.98	−8°	3.5	7.2	0.25	0.78	148°
13°C	5.1	0.62	0.54	97°	2.8	4.9	0.30	0.74	148°
11°C	7.4	0.87	0.42	277°	1.3	9.2	0.021	0.98	268°
10°C	11.2	1.97	0.14	229°	1.3	10.0	0.020	0.98	120°
9°C	13.3	2.14	0.12	240°	5.8	7.9	0.53	0.59	148°
8°C	4.8	0.42	0.66	192°	7.8	12.6	0.90	0.41	54°
From reversing thermometers and Nansen bottles									
	dyn m				dyn m	dyn m			
ΔD 0/300	0.0059	2.84	0.059	202°	0.0034	0.003	1.22	0.30	124°

The measured waves are smooth enough to suggest that they might be recognized in non-serial data, such as BT's taken hourly from vessels underway near and parallel to the coast. Such data might show whether the waves measured here are transient or permanent phenomena, and whether they are found all along the coastline.

Space variations of dynamic height—Table 7 shows dynamic heights at nine stations along the line of the anchor stations, taken at the end of the time series. It is the sort of time-space series of data which *Defant* [1950b] had suggested was seriously roughened by short-period time variations. The observed differences from station to station, 40 mi and about five hours apart, range from 1.7 to 18.2 dynamic cm. At three points along the line we know something about the time variation, from the analysis of the anchor stations.

The largest values in the table are the 18.2 and 13.6 cm by which the value at Station 70.80 exceeds the values at 70.70 and 70.90. Examination of the data shows a different water mass at 70.80, with warmer, less saline water in the upper 250 m than at either of the adjacent stations. The density in the upper layers is far too different from that of the adjacent stations for this dynamic height difference to be the result of a short-period vertical fluctuation of the order of any of those observed at the serial stations. A gradient of 18 cm in 40 mi would be equivalent to a geostrophic surface current of about 0.8 knots, an unusually high value in this region.

That this is space- rather than time-variation is suggested by the dynamic topography of other cruises in this area, where the dynamics are occasionally complex, and somewhat different water masses may be found close together. In these cases usually one of the types will contour as a 'cloud' or closed circle surrounded by a relatively sharp gradient of temperature and salinity.

If these clouds are in geostrophic equilibrium they are eddies, rotating rapidly in the center of a broad, slowly moving current. Such an eddy has been observed [*Fuglister* and *Worthington*, 1951] on the edge of the Gulf Stream, where the momentum is much higher. But if they are not in geostrophic balance they may be non-rotating and moving with the same slow velocity as the rest of the current. In any case, the value of dynamic height at Station 70.80 exceeds the adjacent values by much more than could be explained by any of the time changes on the table, periodic or random.

Time-space variation of dynamic height—The other increments are much more nearly equal. The total change in dynamic height from 72.60 to 70.130 is 23.2 cm. The average change is 3.3 cm. per 40-mi station interval. This is a little more than the root mean square of the greatest changes during 12 hr (column 8), and a little less than the greatest change during any 12 hr (column 7).

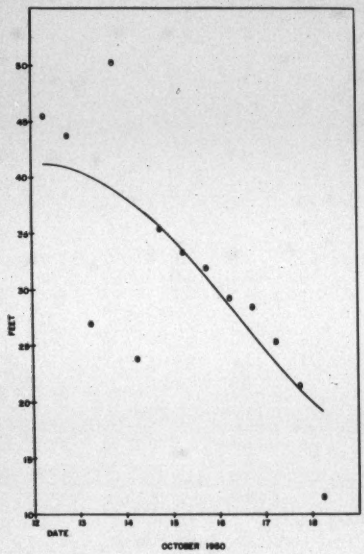

FIG. 4 – Amplitude of M_2 at thermocline

Column 9 shows the root mean square of deviations from the 12-hr means, and column 10 the part of the variations which might have been periodic and hence accounted for in interpretation.

The greatest differences at the time series stations occurred from three to seven days apart. It was not expected that such changes could be eliminated, nor was it desired, since they represent real phenomena and the stations are usually taken not more than six hours apart. At the ends of lines, of course, these intervals may be exceeded by another six hours since the distance between station lines is greater than that between stations on a line, and where the cruise patterns of two ships adjoin the interval may be several days. On occasion two weeks have passed between covering adjacent lines 40 to 120 mi apart. Since these results have become available more serious attempts have been made to work adjacent vessels either away from each other, letting them start together on adjacent lines, or toward each other working until they meet.

Time variations in dynamic height at a station are important if they are of the order of magnitude of the 'average' dynamic height increment to the adjacent stations. Therefore stations should be spaced with a knowledge of the gradient and time variation of dynamic height in each locality as well as according to other considerations. These other considerations may well require a closer spacing of stations than would seem justified for valid interpretation of dynamic height. An example is found in programs where biological sampling may be needed sometimes at ten-mile intervals, and certain hydrographic data desired for each sample.

Suggestions for further work—The results show that at the time of this cruise, at least, corrections to dynamic height could not be made at the outer stations on the basis of known phase and period, as *Defant* [1950ab] had hoped.

To find the distance at which internal tidal waves might keep coherence and to measure the speed it is suggested that two vessels begin quite close together, and only after coherence is established increase the distance.

Conclusions—Clearly defined tidal internal waves were found 40 mi offshore in deep water (1000 fm). They did not appear 120 mi farther out in a recognizable shape, although the non-periodic fluctuations in dynamic height were as great even at 280 mi offshore.

The phase of the measured tidal internal wave was the same as that of the surface tidal wave at the coast 40 mi away, and the amplitude varied with that of the surface tidal wave.

It may therefore be supposed that these tidal

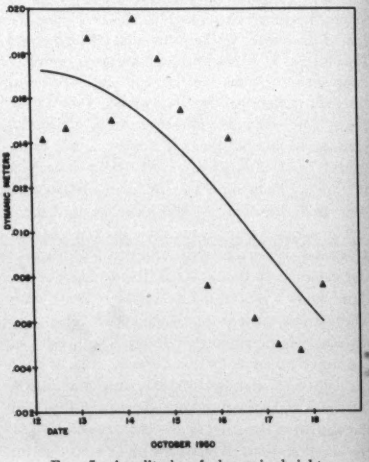

FIG. 5 – Amplitude of dynamic height 0/300 decibars

TABLE 7 – *Dynamic heights, 0/300 db, for the nine stations of Figure 1*

Station	Distance	Time of cast or series	ΔD 0/300	Difference	Greatest range during time series	Greatest range during any 12 hrs.	RMS of 12-hr ranges	RMS of deviations from 12-hr mean	Amplitude of M_2
1	2	3	4	5	6	7	8	9	10
	mi	Oct h m	dyn m	dyn m	dyn m	dyn m	dyn m	dyn m	dyn m
72.60		12 00 00 to 18 09 00	0.581[a]		0.074 (Oct 13–16)	0.034 (Oct 12)	0.026	0.010	0.0111[b]
		18 09 00	0.545						
	30			0.003					
70.60		20 07 49	0.548						
	40			0.056					
70.70		20 03 25	0.604						
	40			0.182					
70.80		19 22 57	0.786						
	40			−0.136					
70.90		19 18 00	0.650						
70.90		11 21 00 to 19 18 00	0.604[a]		0.085 (Oct 12–19)	0.050 (Oct 12)	0.029	0.009	0.0005
70.90		19 18 00	0.650						
	40			0.001					
70.100		20 09 28	0.651						
	40			0.098					
70.110		20 04 29	0.749						
	40			0.047					
70.120		19 23 18	0.796						
	40			0.036					
70.130		19 18 00	0.832						
70.130		11 21 00 to 19 18 00	0.813[a]		0.057 (Oct 14–17)	0.051 (Oct 12)	0.024	0.011	0.0032

[a] Average value for the time series.
[b] Separating M_2 and S_2 by the method described in the text.

internal waves originate near the shore in the surface tides. That they were not found farther out may be the result of attenuation over so many wave lengths due to frictional loss. More likely, since the speed of advance is so low and is dependent upon a complex and constantly varying density structure, and the waves must cross an irregular current, they may be so severely distorted after two or three lengths that they are no longer recognizable as periodic phenomena, even though their energy has not yet been spent.

If these waves are really formed near the coast by the action of the surface tide and have the simple phase relationship shown in this case, then it may be possible to examine long distances of the coast for this phenomenon from data already available.

Other measurements of internal waves in the deep ocean at great distances offshore have shown considerable vertical fluctuations but only in rare cases (and then usually only over short series of measurements) has it been possible to ascribe a periodicity to them. It may be possible that some part of these vertical fluctuations could originate near the coasts, near islands and seamounts or banks, through the action of the surface tides in shallow water.

Acknowledgment—I wish to express my appreciation to Robert S. Arthur for many stimulating discussions and suggestions.

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of Stanford University, and the California Academy of Sciences.

Appendix

Analyzing data tabulated at solar hour intervals for the lunar semi-diurnal period of 12.4206 hours—Certain criteria [*Haurwitz*, 1954] for the reality of the amplitudes associated with a certain period involve determining the amplitude of each cycle separately so that a stepwise analysis is necessary. The extra labor can be reduced if the stepwise analysis can be made to serve for two slightly different periods such as the M_2 and S_2 constituents. This can be done because if one cycle of a 12.4206-hr curve is analyzed for a 12-hr curve the 12.4206-hr amplitude is closely approximated and the differences may be accounted for. Then each 12 hr of the data can be analyzed separately and the resultant set of curves may be then referred to a common time origin and averaged for the final evaluation of the lunar semidiurnal.

In the rare cases where the data justify it, variation of daily amplitudes may be used to separate two constituents.

Numerical evaluation of the coefficients—Any 12 hr of a curve of 12.4206-hr period may be fairly well represented by a 12-hr curve. That is, if

$$y = f(t) = a \cos mt + b \sin mt \qquad (1)$$

where $m = 2\pi/12.4206$, t in hours, we can approximate it by

$$y' = a' \cos nt + b' \sin nt,$$

where $n = 2\pi/12$, by defining

$$\left.\begin{aligned} 6a' &= \int_{-6}^{6} f(t) \cos nt \, dt \\ 6b' &= \int_{-6}^{6} f(t) \sin nt \, dt \end{aligned}\right\} \qquad (2)$$

We see that $a' = 0.9801\ a$, $b' = 1.0141\ b$. If (1) be rewritten to refer to a time L rather than to $t = 0$, it will be, if $t_L = t - L$

$$\begin{aligned} y &= a \cos m(t_L + L) + b \sin m(t_L + L) \\ &= (a \cos mL + b \sin mL) \cos mt_L \\ &\quad + (b \cos mL - a \sin mL) \sin mt_L \end{aligned} \qquad (3)$$

we may determine the approximate curve y_L' for the interval $-6 \leq t_L \leq 6$ by substituting (3) into (2). The resulting coefficients, which depend upon L, are related to a and b by

$$\left.\begin{aligned} a_L' &= 0.9801\ (a \cos mL + b \sin mL) \\ b_L' &= 1.0141\ (b \cos mL - a \sin mL) \end{aligned}\right\} \qquad (4)$$

These can be solved for a and b, designated a_L and b_L since in the data they will vary with L, and

$$a_L = 1.0203\ a_L' \cos mL - 0.9861\ b_L' \sin mL \qquad (5a)$$

$$b_L = 0.9861\ b_L' \cos mL + 1.0203\ a_L' \sin mL. \qquad (5b)$$

In practice a_L' and b_L' are determined from the data by direct harmonic analyses as in (2) and then a_L and b_L determined from (5a) and (5b).

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Subsidence of the Land Surface in the Tulare-Wasco (Delano) and Los Banos-Kettleman City Area, San Joaquin Valley, California

J. F. Poland and G. H. Davis

Abstract—Releveling of bench marks in 1953 and 1954 by the U. S. Coast and Geodetic Survey indicates that subsidence of the land surface has now exceeded ten feet in two areas of the San Joaquin Valley. In the Tulare-Wasco (or Delano) area of Tulare County, subsidence which was as much as five feet in 1940 now has about doubled. The maximum rate of subsidence in recent years has been about 0.8 foot a year. In the Los Banos-Kettleman City area of western Fresno County, major subsidence extends from Ora Loma on the north beyond Huron on the south, a distance of 70 miles or more. The maximum rate there approaches one foot a year. Plots of subsidence against decline in artesian pressure suggest that pressure decline is a major cause of the subsidence. Compaction of the soil after irrigation is known to have caused substantial local subsidence in the Los Banos-Kettleman City area, and tectonic adjustment and other causes also may have contributed to the subsidence.

Introduction

Occurrence of land subsidence—For many years substantial subsidence of the land surface has been occurring at several places in California, in other parts of the United States, and in foreign lands. In California, subsiding areas that have received the most attention are the San Jose area in the Santa Clara Valley [*Tolman* and *Poland*, 1940] and the Wilmington area of Los Angeles Harbor [*Gilluly* and *Grant*, 1949], but the subsidence observed for the longest time (since 1922) has been in the peat lands of the Sacramento-San Joaquin Delta [*Weir*, 1950]. The principal areas of known subsidence in California are shown on Figure 1. Elsewhere, possibly the best known subsidences are in the Houston-Galveston area of Texas [*Winslow* and *Doyel*, 1954] and in the Mexico City area [*Zeevaert*, 1949]. A lesser subsidence has been described in the Lake Mead area [*Longwell*, 1954], and local substantial subsidence in the Heart Mountain Division of the Shoshone Irrigation Project in Wyoming [Swenson, in preparation].

Subsidences in the vicinity of many oil fields also have been described. Of these, the Wilmington subsidence, those in the Goose Creek and Sour Lake oil fields in Texas, and the one in the Lake Maracaibo area of Venezuela probably are the best known. In addition, minor subsidences have been noted at many California oil fields, such as Signal Hill, Huntington Beach, and Santa Fe Springs.

Land subsidence in the San Joaquin Valley—Subsidence of the land surface in the San Joaquin Valley was first described in 1941 by *Ingerson* [1941] who reported briefly on the subsidence in the Delano (Tulare–Wasco) area. Since that time subsidence has been observed in at least two additional areas: The Los Banos–Kettleman City area and the Arvin–Wheeler Ridge–Maricopa area. Information on the magnitude of these subsidences is available chiefly through first-order leveling and releveling of the U. S. Coast and Geodetic Survey, but supplementary leveling is available from several other agencies, especially the United States Geological Survey, the Bureau of Reclamation, and the California Division of Water Resources. Control is best in the Tulare–Wasco area and poorest in the Arvin–Wheeler Ridge–Maricopa area. These principal areas, in each of which several feet of subsidence is known to have occurred, are outlined on Figure 1.

This paper presents information on the status of subsidence in the Tulare–Wasco (Delano) and Los Banos–Kettleman City areas, the two areas of greatest subsidence, as of 1954. In each of these areas, subsidence is known to have exceeded ten feet. Figures 2 and 3 show the extent of subsidence in the Tulare–Wasco area from 1948 to 1954 and in the Los Banos–Kettleman City area from 1943 to 1953. These subsidences occur in irrigated areas traversed by costly canals of large capacity and low gradient, and additional trunkline and distribution canals are proposed. The extent, magnitude, and rate of subsidence and amount of future subsidence (or recovery of land surface) are of paramount importance in planning construction or repair of such structures.

Subsidence in the Tulare – Wasco (Delano) Area

General features—The Tulare – Wasco area is in the southeastern part of the San Joaquin Valley, chiefly in Tulare but extending south into Kern County. The town of Pixley in the northern part of the subsidence area is roughly equidistant from

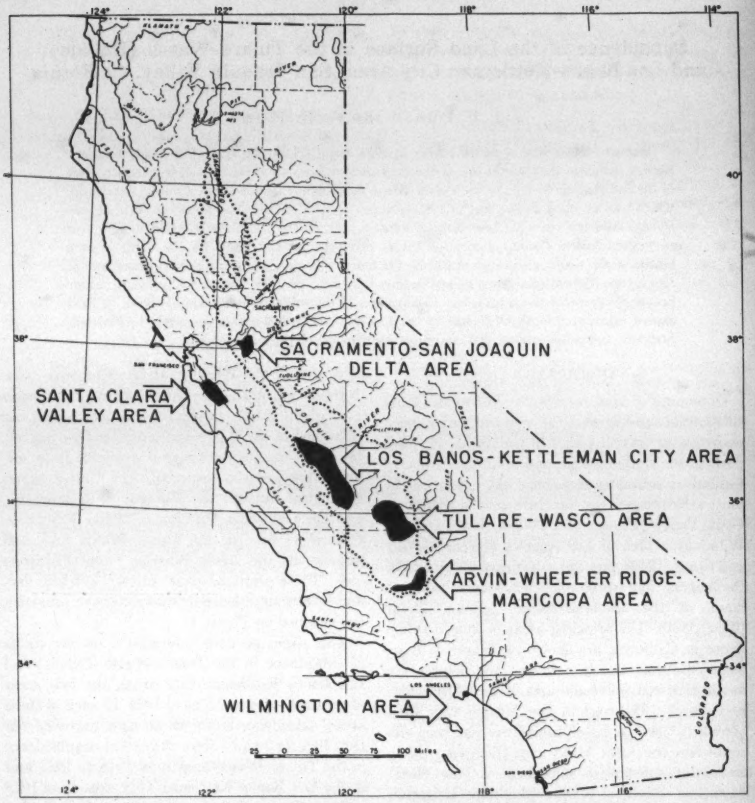

FIG. 1 – Areas of land subsidence in California

Fresno and Bakersfield, and the area of subsidence is nearly bisected by U. S. Highway 99 and the Southern Pacific railroad. Delano is the largest city within the area of substantial subsidence. The area is agricultural and much of it is irrigated, until 1950 almost wholly from wells but since then in part by water imported from the San Joaquin River through the Friant – Kern Canal.

Wells have been used for irrigation in Tulare and Kern Counties since about 1885 [*Mendenhall* and others, 1916], and much of the subsiding area is irrigated by water from wells at the present time. Because of increased pumping demand and the deficient local supply, water levels have declined for many years. In spite of the scope of the groundwater development, however, the geology and hydrology of the Tulare – Wasco area are not well known.

In a field examination of wells in 1905–07 *Mendenhall* and others [1916, pl. 1] found that the area of flowing artesian wells extended east from Tulare Lake about to a line through Tulare, Pixley, and Earlimart, about two miles west of Delano and three miles west of Wasco. Thus, even in 1905 it was known that an extensive area of confined water underlay the western part of both counties. Recent work by the Bureau of Reclamation and others has shown that the principal confining bed is a diato-

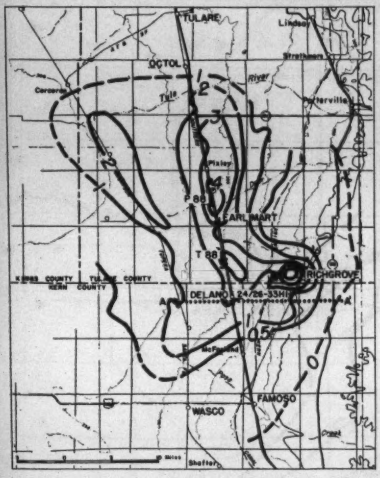

FIG. 2 – Land subsidence, Tulare-Wasco (Delano) area, 1948–54 (lines of equal subsidence in feet)

maceous clay at a depth of several hundred feet below the land surface. This clay, which is the principal confining bed beneath several thousand square miles of the San Joaquin Valley, separates unconfined and semi-confined water above from confined water beneath; it extends about a mile east of Earlimart and Delano. The separation of water bodies extends farther east, however, possibly owing to the presence of other confining beds in the section tapped by water wells.

Water levels in the Tulare – Wasco area have declined substantially from 1905 to date. For example, at Delano the 1905 water-level altitude was approximately 285 ft above sea level. In 1921 it was about 275 ft, but by 1952 the water table had declined to about 190 ft and the pressure head in deeper zones was at about 160 ft. At Richgrove in 1905 the altitude of the water level was about 340 ft, in 1921 it was about 325 ft, and in 1952 it was about 110 ft above sea level. Thus, there had been an overall decline of head in confined aquifers of about 125 ft at Delano and 230 ft at Richgrove, very largely since 1921.

Subsidence—Subsidence of the land surface in the Tulare – Wasco area was first described in print by *Ingerson* [1941, p. 40–42], who noted that in 1935 I. H. Althouse, Consulting Engineer, Porterville called attention to the possibility of a definite subsidence of land surface in the vicinity of Delano. The map prepared by Ingerson indicating lines of equal subsidence from 1902 to 1940 showed the one-foot subsidence contour passing through Pixley and McFarland and a maximum subsidence of five ft half a mile east of U. S. Highway 99 (Southern Pacific R. R.) and three miles north of Delano. Profiles of subsidence and of depth to ground water along the Southern Pacific R. R. were presented.

Precise leveling in the area was carried out first in 1902 by the U. S. Geological Survey. A first-order line was established in 1930–31 by the U. S. Coast and Geodetic Survey along the Southern Pacific R. R., and this line and others were releveled by the same agency in 1940 and 1943. Because these relevelings and levels run by other agencies showed continuing subsidence, at the request of several agencies the U. S. Coast and Geodetic Survey in 1948 established a level net designed to give reasonably close control in the area of known subsidence. This control net was releveled between December 1953 and March 1954. Subsidence of the land surface as indicated by changes of elevation of bench marks from 1948 to 1954 is shown by lines of equal subsidence on figure 2. The area enclosed by the one-ft subsidence line approximates 450 sq mi. The subsidence during the six-year period ranged from nothing south of Famoso and along the eastern margin of the valley to more than four ft between Earlimart and Pixley and in an area west of Richgrove. Figure 2 shows also the location of profiles, bench marks, and wells to be discussed.

Changes in elevation of bench marks along the Southern Pacific R. R. from Octol to Famoso for the period 1902 to 1954 are shown on Figure 4. Levelings in 1902, 1931, 1940–43, 1948, and 1954 indicate that the maximum subsidence along the line has been 10.2 ft since 1902 at bench mark T 88, about four miles north of Delano, although the maximum subsidence from 1948 to 1954 was recorded at bench mark P 88, between Pixley and Earlimart. Subsidence at P 88 totaled 4.7 ft during the six-year period, indicating an average rate of about 0.8 ft per year.

Subsidence of the land surface and change in head in the confined aquifers along line A-A′ (Fig. 2) are compared on Figure 5. The lower profiles show the altitude of the piezometric surface of the confined water along most of line A-A′ in 1948, 1952, and 1954. Comparison of the profile for 1952 with that for 1948 indicates decline in head all along the profile, but comparison of the profile for 1954 with that for 1952 shows substantial recovery

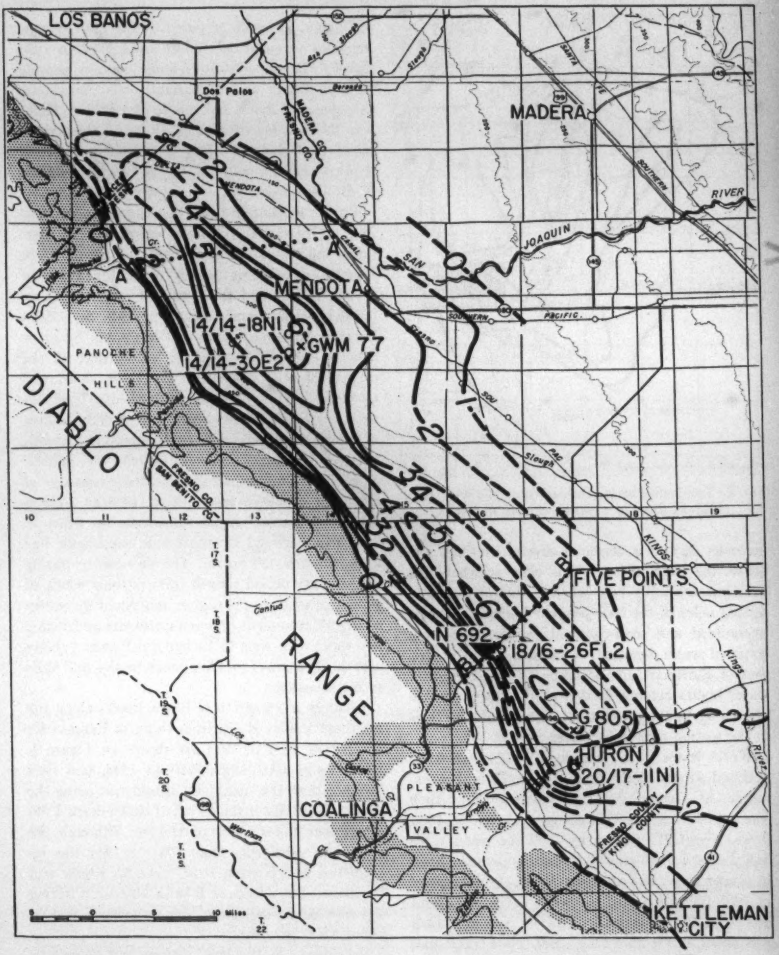

FIG. 3 – Land subsidence in the Los Banos-Kettleman City area, 1943–53 (lines of equal subsidence in feet)

in the area east of Delano. This recovery, which evidently is related to importation of new surface-water supplies to the area via the Friant–Kern Canal, even appears as a net rise of about five ft for the period 1948–54 about 1½ miles east of Delano. The graphs of subsidence and change in head agree fairly closely in the vicinity of Delano, but near the eastern end of the profile of water-level change a marked discordance is evident. This decrease in the ratio of subsidence to decline in head is not fully understood. It may well be related to a change in the elastic or other physical properties of the sediments, or may represent a decrease in the degree of confinement to the east;

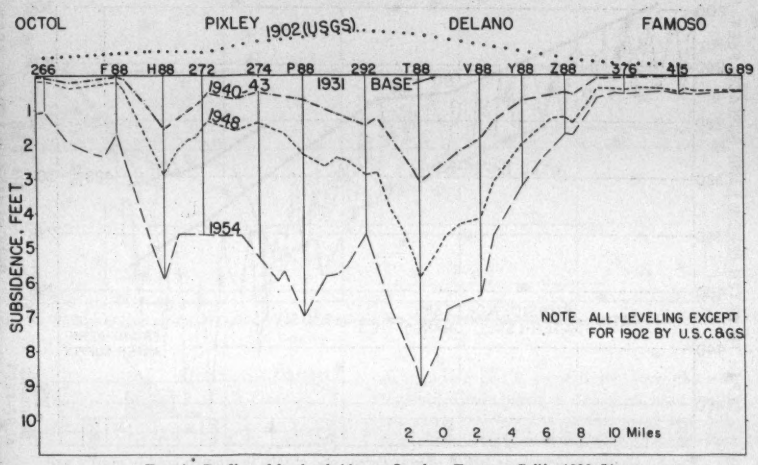

FIG. 4 – Profiles of land subsidence, Octol to Famoso, Calif., 1902–54

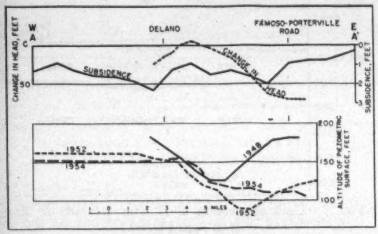

FIG. 5 – Profiles showing land subsidence and change in artesian head along Kernell Road south of Delano, 1948–54 (for location of line A–A', see Fig. 2)

it may also represent a time lag of several years in adjustment to changes in head.

Figure 6 shows changes in altitude at bench marks T 88 and G 758 and change in pressure head in well 24/26-33H1 (see Fig. 2). The hydrograph of well 24/26-33H1, about five miles northeast of Delano shows seasonal fluctuations and the long-term water-level trend since 1930 in a typical well tapping the confined aquifers. It shows a continuing decline from 1930 to 1951, evidently the result of overdraft on local supplies of ground water. After the beginning of delivery of imported water by the Friant–Kern Canal (Fig. 6), however, the long-term trend began a pronounced rise which continued through 1954. Bench mark T 88 is six miles west of well 33H1. The graph for this bench mark, based on leveling in 1931, 1940, 1943, 1948, and 1954, shows good correlation with change in head in well 33H1 except after 1951, when the water level in the well began to rise but the bench mark continued to subside. The graph for bench mark G 758, only half a mile from the well, based on leveling in 1948, 1951, and 1954, however, indicates a lessening of the rate of subsidence between 1951 and 1954 as compared with 1948 to 1951, possibly as a result of recovery of artesian pressure after 1951.

SUBSIDENCE IN THE LOS BANOS–KETTLEMAN CITY AREA

General features—The Los Banos–Kettleman City area is in the west-central part of the San Joaquin Valley, almost wholly in Fresno County but extending north into Merced County and south into Kings County. The area is about 90 miles long and extends from the western edge of the valley about to Fresno Slough and the San Joaquin River, an average width of about 16 miles. Most of the area is irrigated by ground water pumped from approximately 1000 irrigation wells; only north of the Delta–Mendota Canal is surface-water irrigation extensive. Most of the ground-water development has occurred since 1940 and pumpage tripled from 1945 to 1953. In 1953 it was about 1,200,000 ac ft [*Davis* and others, 1954].

The deposits containing fresh water in this area

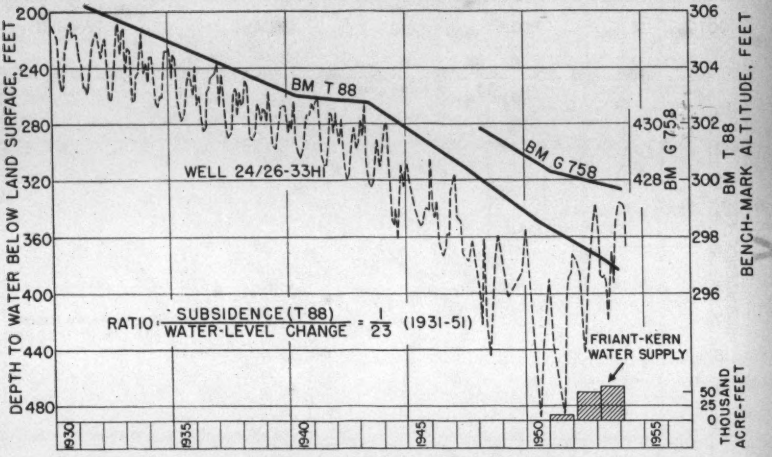

FIG. 6 – Change in altitude at BM T 88 near Delano and change in artesian head in nearby well

are of Recent to Pliocene age and extend to depths ranging from less than 1000 ft to at least 3000 ft below the land surface. They can be divided into (1) an upper unit of clay, silt, and sand, chiefly alluvial-fan deposits, that extends from the land surface to depths of 400 to 800 ft; (2) a middle unit of impervious diatomaceous clay 20 to 120 ft thick; and (3) a lower unit of clay, silt, and sand, in part of lacustrine origin, commonly 600 to 1500 ft thick but locally as much as 2500 ft thick, that extends down to beds containing saline water.

A body of semiconfined water occupies most of the upper unit; the water table at its top is ten to 300 ft below the land surface. The ground water in the lower unit, the lower water-bearing zone, is confined in most of the area by the diatomaceous clay. Probably 80 pct or more of the pumping draft is from this lower zone. The general positions of the upper and lower water-bearing zones and of the diatomaceous clay that separates them, as encountered along line A-A′ (Fig. 3), are shown on Figure 7.

The water table in the upper water-bearing zone has not changed greatly from its initial position. However, the heavy pumping draft has drawn down the pressure head in the lower water-bearing zone as much as 300 ft in the past 20 years; the decline has ranged from 150 ft near Mendota on the northeast to roughly 300 ft near Huron on the south. Since 1945 the average rate of yearly decline has been four to seven feet in the northern

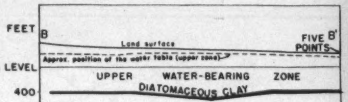

FIG. 7 – Geologic section B–B′ (for location of line B–B′, see Fig. 3)

part and 20 to 30 ft in the southern part of the area.

Subsidence—Subsidence of the land surface in the Los Banos–Kettleman City area was noted as early as 1943, when releveling by the U. S. Coast and Geodetic Survey of bench marks established in 1935 indicated changes in altitude of several feet in some areas. Subsequent levelings by the Coast and Geodetic Survey in 1947, 1953, and 1954 and by the Bureau of Reclamation, the Geological Survey, and the California Division of Water Resources have supplied the data for the map showing subsidence from 1943 to 1953 (Fig. 3). The land-surface subsidence is shown by generalized lines of equal subsidence based on leveling along widely separated lines. Approximately 1050 sq mi is enclosed within the one-foot subsidence line. Two areas of sharp subsidence in which the decline exceeded six feet during the

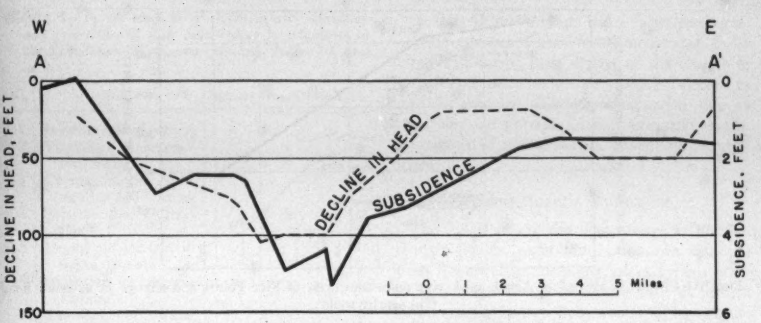

FIG. 8 – Profiles of land subsidence and decline in artesian head from Little Panoche Creek east to Benito, 1943–53 (for location of line A-A', see Fig. 3)

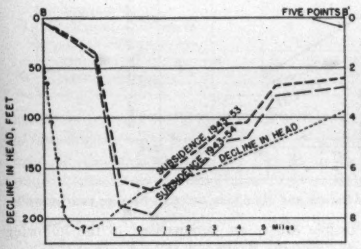

FIG. 9 – Profiles of land subsidence and decline in artesian head along Fresno-Coalinga Road southwest from Five Points, 1943–53

ten-year period 1943 to 1953 are shown on Figure 3, one in the southern part of the area centered about 4½ miles north of Huron, and the other in the northern part of the area centered about seven miles southwest of Mendota. The maximum subsidence recorded was at bench mark G 805, 2½ miles north of Huron, which declined about 7.5 ft between 1947 and 1954. (Unadjusted preliminary elevations, 1954, by U. S. C. and G. S. adjusted 0.8 foot downward to make previously stable area in Kettleman Hills stable with respect to valley area.) The maximum subsidence from 1943 to 1953 in the northern area occurred at bench mark GWM 77, about 7½ miles southwest of Mendota, which declined 6.8 ft. Bench mark 246 USGS, about four miles north of GWM 77, apparently subsided 5.7 ft between 1919 and 1943, thereby suggesting a total subsidence in the northern area of about 12 ft.

Profiles of land subsidence and decline in artesian head of the lower water-bearing zone along lines A-A' and B-B' of Figure 3, presented on Figures 8 and 9, respectively, show the relationship of subsidence to decline in head in the ten years 1943–53. The profiles along line A-A' (Fig. 8) indicate a rude correlation; the maxima on both profiles are about coincident, although the ratio of subsidence to decline changes along the profiles. Figure 9 shows subsidence from 1943 to 1954, based on precise leveling, and subsidence for the ten-year period 1943–53, extrapolated from the 1943–54 change on the basis of rate of subsidence at bench mark N 692 since 1947 (Fig. 10). The graphs of subsidence and decline in head correspond reasonably well except that the trough of maximum subsidence is about 2½ miles east of the trough of maximum decline in head. The pressure trough, however, has been migrating westward with recent development of land along the western edge of the valley and accompanying heavy draft on ground water, and the subsidence trough also may be migrating with a lag as indicated.

Changes in altitude of bench marks of maximum subsidence in the areas of heaviest subsidence and of pressure levels in nearby wells are illustrated on Figures 10, 11, and 12, respectively. Bench marks GWM 77 and N 692 have behaved similarly, both showing a pronounced increase in the rate of subsidence since 1947. The pressure head of the confined water in the lower water-bearing zone also has been declining at an accelerated rate in recent years as a result of rapid development of irrigation in the area since the close of World War II. This accelerated rate of decline is well shown by the composite hydrograph of well 18/16-26F1 and F2 (Fig. 10). The plot of bench mark G 805 (Fig. 12) is based on only two levelings and was included merely to show conditions in the area of greatest ten-year subsidence, but leveling to other bench

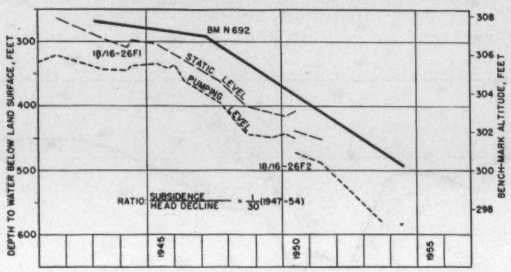

FIG. 10 – Change in altitude at bench mark nine miles southwest of Five Points and change in artesian head in nearby wells

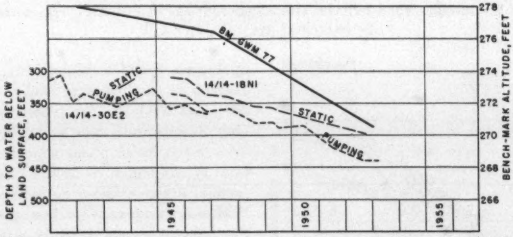

FIG. 11 – Change in altitude at bench mark southwest of Mendota and change in artesian head in nearby wells

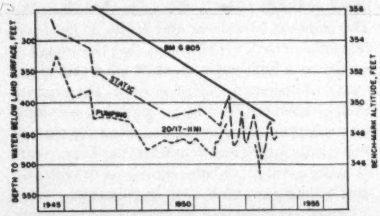

FIG. 12 – Change in altitude at bench mark near Huron and change in artesian head in nearby well

marks in the vicinity suggests that the rate of subsidence there also has been increasing in recent years. All three of the figures suggest a general correspondence between the trend of land-surface subsidence and pressure decline. The ratio of subsidence to pressure decline as shown on Figure 10 for the seven years 1947–54 was 1/30. In the Tulare–Wasco area the corresponding ratio shown on Figure 6 from 1931 to 1951 was 1/23.

CAUSES OF SUBSIDENCE

Subsidence of the land surface has been noted in many areas and ascribed to various causes. Possible causes are summarized in the following table and the likelihood of each cause being responsible for or a contributor to subsidence in the Los Banos – Kettleman City and Tulare–Wasco areas is indicated on Table 1.

In considering these possible causes, note: (1) There has been no general loading of the land surface with structures in the areas of subsidence. (2) The only widespread vibrations at or near land surface in the areas have been from land cultivation, from the drilling of water wells, and from infrequent earthquakes. Locally in the Tulare–Wasco area, vibrations from the passing of railroad trains have occurred many times each day. (3) There is good evidence that compaction due to application of irrigation water is a contributing cause. (4) It seems probable that solution is a contributing but minor cause. (5) Excessive and sustained drying does not ordinarily occur in irrigated areas. (6) Soils in these areas do not contain a high percentage of organic matter. (7) The water table has not declined appreciably in the Los Banos–Kettleman City area; in areas where it has declined and the confining beds are continuous and relatively impermeable, the resultant removal of load from deeper aquifers that

TABLE 1 – *Possible causes of land-surface subsidence and probability of their contributing to subsidence in the Los Banos - Kettleman City and Tulare - Wasco areas*

No.	Item	Unlikely	Possible	Probable
1	Loading at land surface	x		
2	Vibrations at or near land surface		x	
3	Compaction due to irrigation and farming			x
4	Solution due to irrigation		x	
5	Drying out and shrinking of deposits	x		
6	Oxidation of organic material	x		
7	Lowering of water table		x	
8	Decline of pressure head in confined aquifers			x
9	Decline of pressure in oil zones due to removal of oil and gas		x	
10	Tectonic movement		x	

are under pressure would tend to offset the effects of lowering the water table. (8) Decline of pressure head in confined aquifers has proved to be a major factor in several other areas, and available evidence suggests that it should be considered so in these areas. (9) Producing oil and gas fields are located in or adjacent to part of the subsidence areas, and decrease in fluid pressure due to removal of oil and gas would be a contributing cause. (10) Tectonic activity has been demonstrated to be responsible for at least a portion of the movement in the Arvin–Wheeler Ridge–Maricopa area, but whether it has contributed appreciably to subsidence in the two principal areas discussed in this paper is not yet known.

On the basis of presently available data it is concluded that the extensive drawdown of the confined water has been one of the primary causes if not the major cause of subsidence in the Los Banos–Kettleman City and Tulare–Wasco areas. Field reports of noticeable settlement of the land surface of as much as several feet in the vicinity of wells and ditches on newly irrigated land on the west side of the San Joaquin Valley suggest that, locally at least, compaction due to irrigation and farming is a major cause of settlement. However, no specific measurements of subsidence of this nature are yet available to assist in evaluating its relative importance in the regional subsidences here discussed. In addition, it is considered that six other possible causes may contribute to the overall land-surface subsidence.

In the Arvin–Wheeler Ridge–Maricopa area, tectonic movement has been demonstrated to be responsible for at least a part of the change in land-surface altitude, but very possibly decline in head in confined aquifers, compaction due to irrigation, and decrease in fluid pressures due to the removal of oil and gas also contribute to subsidence.

INTER-AGENCY COMMITTEE

The subsidence of the land surface in the San Joaquin Valley, especially in the two principal areas described in this paper, poses serious problems in connection with maintenance of present large-capacity low-gradient canals and construction of proposed additional canals, as well as in construction and maintenance of other engineering structures such as irrigation distribution systems, trunk pipelines, drainage and sewerage systems, power-transmission lines, highways, railroads, and buildings, and in various aspects of land development and use. The Bureau of Reclamation already has large canals in each of the two areas, and largely at the suggestion of that agency an Inter-Agency Committee of interested Federal and State agencies has been formed for the purpose of formulating and carrying out a program designed to furnish information on the extent, magnitude, rate, and causes of the land subsidences in the San Joaquin Valley, in order that planning and construction agencies may be able to estimate with fair accuracy the location, rate, and magnitude of future subsidence (or recovery) of the land surface.

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An Evaluation of Ground-Water Tracers

W. J. KAUFMAN AND G. T. ORLOB

Abstract—The ideal ground-water tracer should correctly depict the movement of water through a porous medium without modifying the transmission characteristics of the system. Cationic materials, including radio-isotopes and certain organic dyes, are generally unsatisfactory and anionic radio-isotopes when used without stable carriers may be largely retained by adsorption. Chloride may be satisfactorily used where density effects can be avoided and dispersion of clays is not likely. Organic materials are subject to decomposition by soil microorganisms and hence their value as water tracers are limited. Tritium, when used as tritiated water, may exchange with soil bound water with a resulting reduction in velocity of the tracer front.

The measurement of velocity and direction of fluid flow through porous media have been of concern to the hydrologist, soil mechanician, petroleum engineer, and the sanitary engineer for more than half a century. The early work of *Slichter* [1905], who used solutions of various salts and measured the time of tracer-front arrival by changes in resistivity of ground water, produced one of the first accepted techniques for estimation of underflow. More recently the use of injection wells by the petroleum industry for flooding depleted reservoirs as a means of secondary recovery has stimulated interest in methods of tracing the movement of recharged fluids. Restrictions placed by state regulatory agencies on the discharge of water unfit for human consumption into underground aquifers suitable as domestic water sources has further increased the need for more reliable methods of determining of nature of liquid movement through soil voids. Perhaps the most recent attention given this subject stems from the need for a safe, economical disposal method for the wastes of a developing nuclear power industry. Permanent storage of long-lived fission products in connate water-bearing strata has been suggested as a possible solution to this problem. Seepage through earth dams, leakage from irrigation canals, and the intrusion of sea water into fresh water strata are other examples where a more thorough understanding of rate variations of fluid movement through permeable media is desirable.

The major velocity variation occurring during the movement of fluids through a complex system of voids in naturally formed porous strata is particularly dependent on the anisotropic and heterogeneous character of the medium. While it is often possible to estimate a mean frontal velocity for Darcy's law and the porosity of the medium, it is readily apparent by inspection of a typical tracer breakthrough curve that all portions of the front do not move at the same velocity. Neglecting any interaction between tracer component and the porous medium, the degree of front dispersion or dilution along the axis of flow may be considered as a function of several individual phenomena, as follows:

(1) Gross or macroscopic variations in permeability may result in channeling, of 'fingering,' causing very rapid travel of portions of the tracer front, while other portions of the front may actually be retarded. Such fingering may be either longitudinal or transverse to the major direction of flow.

(2) Minute, or microscopic variations in permeability, resulting from the differing diameters of adjacent pores, will cause velocity differences from pore to pore, and increase the length of the front.

(3) Velocity distribution within a single capillary will cause further longitudinal dispersion with additional lengthening of the front.

(4) Molecular diffusion in the direction of flow is probably of relatively small significance except in cases where the actual linear flow rate is extremely small. However, diffusion transverse to the direction of flow may be a significant factor in determining frontal characteristics.

(5) The presence of non-transmitting interstitial cavities connected to water transmitting pores by small openings may permit the interception and retention of a portion of the tracer by diffusion. This mechanism will also be operative in defining the shape of the elution limb of the transient tracer curve by the subsequent release of the captured tracer after the principal front has passed.

Several investigators have attempted to define the velocity of water movement in terms of the arrival time of some point on the breakthrough curve. *Slichter* [1905], for example, has used the inflection point as an indication of average velocity. Other investigators, interested in velocity of pollution travel underground [*University of California*, 1954], have been concerned with the time of first

arrival. Neither of these points, however, can be easily defined, particularly if the distance of travel is great or the medium shows gross non-uniformities. Since the studies reported herein were not concerned primarily with the delineation of microscopic velocity variations but rather with comparing the efficiency of various tracers, it was convenient to employ the arrival times of relative tracer concentrations of ten and 50 pct. Using these points it is also possible to obtain a measure of front dispersion or elongation during the course of tracer movement through the medium.

An ideal tracer should correctly describe the velocity variations of the liquid being traced without modifying in any way the transmission characteristics of the liquid-porous medium system. It is essential that the tracer be detectable in low concentrations in order to minimize changes in soil structure or liquid properties which might modify the permeability. A further requisite is that the tracer should not be retained on the solid phase by adsorption or ion exchange, since this in turn results in a retardation of the tracer front. Theoretically, no tracer can exist that will completely meet all of these requirements. Practically, it should be possible to select a reasonably satisfactory tracer to meet the needs of a particular situation.

The objectives of this preliminary study have been to investigate the interaction of certain organic, inorganic, and radioactive tracers with several typical California soils and to develop criteria by which the adequacy of a water tracer may be ascertained. It was desired to demonstrate the particular limitations of radioactive elements used as tracers and to determine ultimately the most satisfactory radionuclide for this purpose.

With commercially available equipment, radioisotopes can be measured by their nuclear radiations at mass concentrations of 10^{-18} or even less. At such low concentrations radioactive tracers can have no effect on liquid or media properties. Similarly, certain organic dyes, such as fluorescein, can be detected in extremely minute concentrations and would be expected to exert a negligible influence on permeability coefficients. Both of these tracer types meet the hydrodynamic requirements of the ideal tracer but conversely both are subject to limitations in terms of soil capacities for adsorption of minute tracer concentrations.

As a liquid containing a transient trace component enters a porous medium having the capacity to adsorb the component, the liquid is supersaturated with respect to the solid and deposition takes place. The liquid and tracer fronts will cease to move at the same average rate. As fresh liquid, devoid of the trace component, comes into contact with the tracer-medium complex, the liquid is undersaturated- and desorption occurs. This phenomenon may be termed ion exchange chromotography or elution separation and can be utilized to separate elements having different partition coefficients with respect to the solid phase. The ratio of the velocity of the tracer front to that of the liquid has been formulated for organic resins by *Vermeulen* and *Hiester* [1952].

$$\frac{u_A}{U} = \frac{1}{1 + D_A} \tag{1}$$

and

$$D_A = \frac{q_A \rho_b}{c_A f_E} \tag{2}$$

where u_A and U are the velocities of tracer A and the liquid respectively.

q_A = milliequivalents of trace component adsorbed per gram of the solid phase
ρ_b = bulk density of the porous medium
c_A = concentration of A in milliequivalents per cubic centimeter of the liquid phase
f_E = porosity ratio

If (1) and (2) are considered applicable to soil columns exposed to a constant volumetric flow rate, they can be used to illustrate the unsuitability of cationic chemical and radioactive tracers in defining the microscopic velocity variations within a liquid-porous medium system.

Eq (1) may be developed by assuming a liquid lamina of volume $f_E\,dx$ moves slowly a distance dx through a porous medium, transporting $c_A f_E\,dx$ units of the trace component. The trace component becomes distributed between the liquid and solid phases and if the distribution is assumed to reach an equilibrium almost instantaneously, the tracer lamina will move a distance $K\,dx$ such that

$$c_A f_E\,dx = q_A \cdot \rho_b K\,dx + c_A f_E K\,dx$$

in which K is the velocity ratio u_A/U.

If the solid has no capacity to adsorb the tracer, q_A is zero; the ratio u_A/U becomes unity; and the tracer and liquid fronts move together. Similarly, if the tracer is a radioisotope, of which stable forms are present in the liquid and solid phases, the radio-element will proceed toward a similar distribution between the two phases and will accordingly move at a lesser rate than the liquid front. If the adsorption and desorption processes proceed instantaneously, the tracer front will have the same length or sharpness as that of the liquid, being de-

layed only in time. Since exchange reactions have definite effective rate constants, the tracer front may not only be delayed but also may become more diffuse. *Vermeulen* and *Hiester* [1952] report that the nature of the front for resins will be determined in part by an equilibrium parameter r_A which is defined for ions of the same valence as

$$r_A = \frac{c_B + c_A}{c_B + K_A c_A} \tag{3}$$

in which c_A and c_B are the tracer and the carrier concentrations respectively. K_A is the equilibrium constant for the reaction

$$A + B\cdot\text{solid} = B + A\cdot\text{solid}$$

When A and B have the same valence

$$K_A = \frac{q_A c_B}{c_A q_B} = \frac{D_A}{D_B} \tag{4}$$

In the case of radioisotopic tracers, c_A is extremely small compared to c_B and the equilibrium parameter, r_A, is then nearly equal to unity. Under such circumstances the 'break-through' or advancing portion of the tracer front is the complement of the elution, or trailing portion. As the linear flow rate and particle diameters are reduced the front becomes sharper since equilibria are more quickly and completely reached. When exchange-adsorption phenomena are operative, sharpness of the front is accentuated by increased distances of tracer movement through a porous medium. In contrast, front sharpness has been shown to diminish with increasing distance over which purely hydraulic parameters are permitted to operate [*Licastro*, 1951; *Yuhara*, 1951].

If the tracer is added in a sufficient concentration to constitute a relatively significant portion of the exchangeable material present in the liquid, the equilibrium constant K_A may influence the break-through and elution curves. When the tracer is strongly held by the solid, that is K_A is large, r_A will be less than unity and the break-through front will be relatively steep. Conversely, if the tracer is weakly held by the solid phase, K_A will be small, r_A will be large, and the break-through front will become more diffuse and the elution curve will become sharper.

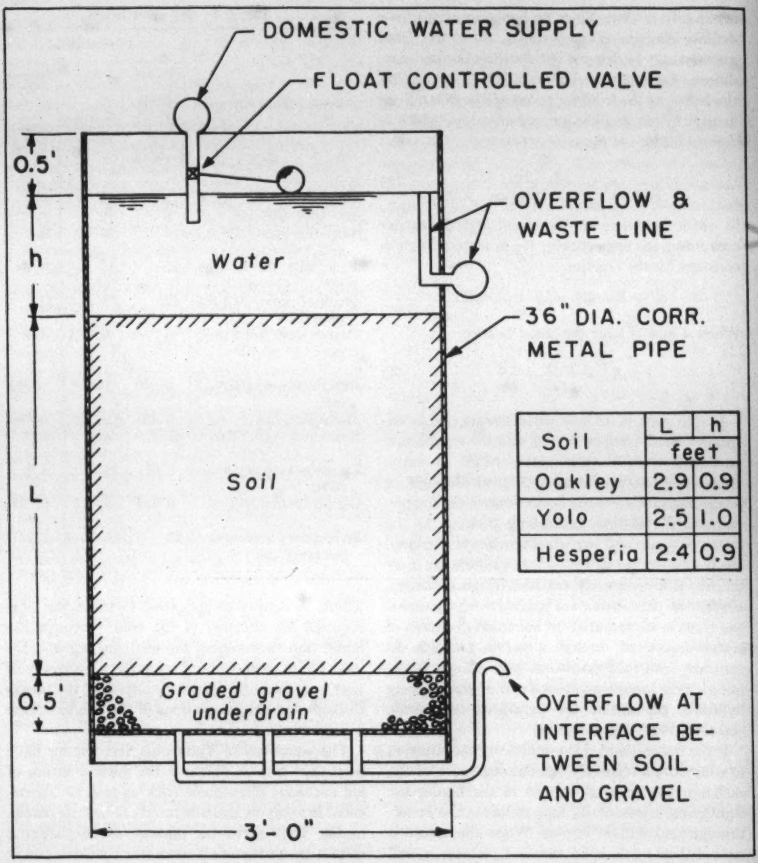
It should be apparent that when permeabilities and flow rates are low, often indicative of a large clay fraction, the solid phase may have a considerable capacity for the trace component. This is particularly significant for cationic tracers but may also be a determining factor in the use of certain anionic materials; for example, radioactive iodine. A further complicating factor is the time required for diffusion of the tracer through the liquid film surrounding the medium and into the solid phase to the site of sorption, a requirement that may cause additional distortion of the break-through and elution portions of the concentration history curve.

TABLE 1 – *Soil characteristics*

Particle size and other items	Parent material		
	Oakley	Yolo	Hesperia
	Sandy mixed alluvium, wind modified (slightly acid)	Sedimentary alluvium (neutral)	Granitic (neutral)
Clay <0.002 mm, pct	5	3	10
Silt 0.002–0.05 mm, pct	9	19	24
Very fine sand 0.05–0.1 mm, pct	15	20	18
Fine sand 0.1–0.2 mm, pct	26	33	29.5
Medium sand 0.2–0.5 mm, pct	42	24.5	11
Coarse sand >0.5 mm, pct	3	0.5	7.5
Effective size (Hazen) mm	0.020	0.021	0.002
Modal size, mm	0.205	0.170	0.180
Uniformity coeff. (Hazen)	11.2	8.1	67.3
Exchange capacity, me/100g	3.01	14.4	8.9
Carbon content, pct	0.055	0.412	0.327
Permeability in place in lysimeter, darcy	82	16	2.2

The equations of Vermeulen and Hiester have been used here to illustrate the general nature of ion exchange phenomena such as may be experienced in applying cationic tracers to natural porous media. They serve the purpose of disqualifying certain tracer materials when due consideration is given to the possible interaction between tracer component and solid phase. It would generally be impractical to attempt accurate evaluation of tracer retardation except under the most closely regulated conditions.

Experimental results—Laboratory studies were carried out with three typical California soils, Oakley sand, Yolo sandy loam, and Hesperia sandy loam. The characteristics of these media are shown in Table 1. After coarse screening the soils were placed in three-foot diameter lysimeters (Fig. 1) and allowed to consolidate under their own weight. The initial depth of dry soil in each



Soil	L	h
	feet	
Oakley	2.9	0.9
Yolo	2.5	1.0
Hesperia	2.4	0.9

FIG. 1 - Typical soil lysimeter

column was three feet; the final depths at the time of the tracer studies are shown in Figure 1. Columns were operated with tap water for several months prior to the tracer runs. The principal tracers studied on each of the three soils were fluorescein, chloride, and iodine-131 as the iodide. Additional investigations were carried out on the Yolo sandy loam using dextrose, calcium, calcium-45, and tritium.

In preparation for each study a sufficient quantity of the tracer was mixed with the water volume above the soil surface to provide the desired tracer concentration. Immediately after mixing, the influent water supply was shut off and the tracer was permitted to move into the column. At the time of first exposure of the soil surface the influent supply was turned on and the water level over the soil returned to normal. Samples were taken from the column effluents at regular intervals during the run. In studies using chlorides, calcium, or sodium fluorescein, a sodium-calcium ratio equal to that of the influent water was main-

tained by addition of appropriate amounts of the chlorides of sodium and calcium.

Data depicting concentration histories of the column effluents for the first series of nine runs are shown in Figures 2, 3, and 4 and summarized in Table 2. A number of general observations may be noted relative to the passage of the three tracers through the three soils, as follows.

(1) The chloride front proceeded at the greatest velocity in every instance and exhibited the least distortion and the sharpest elution curve. The volume through-put corresponding to the initial

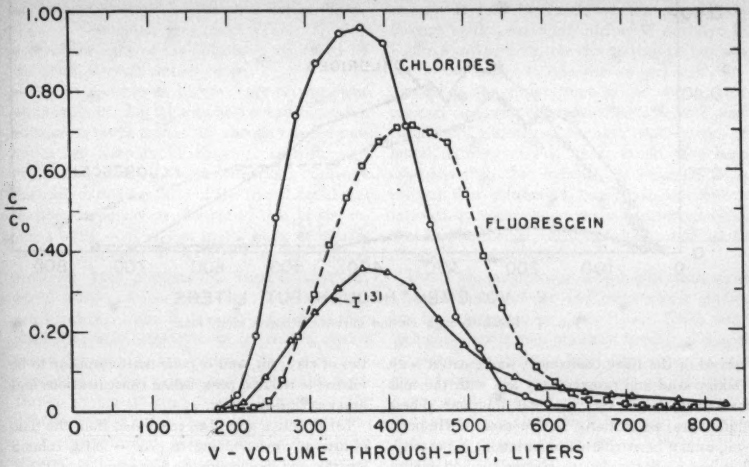


FIG. 2 – Break-through elution curves, Oakley sand

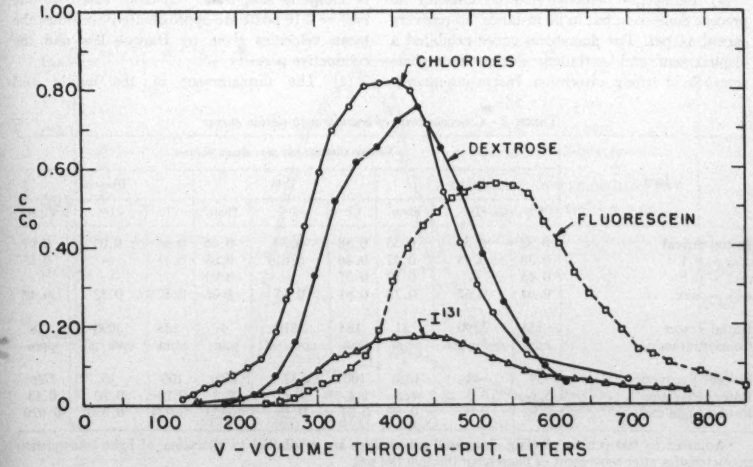


FIG. 3 – Break-through elution curves, Yolo sandy loam

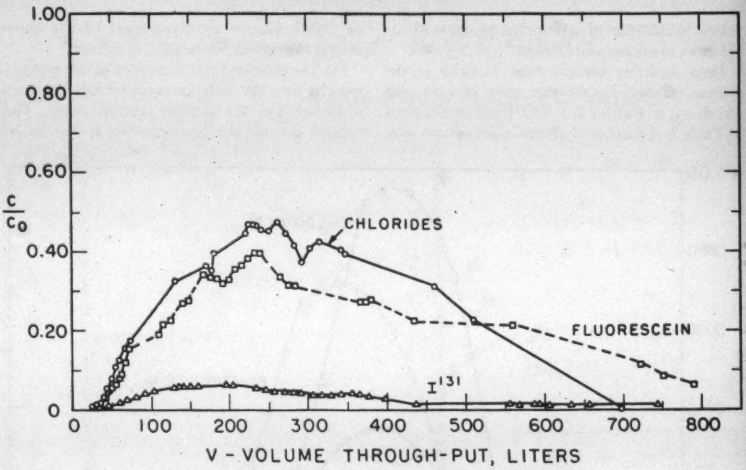


FIG. 4 – Break-through elution curves, Hesperia sandy loam

arrival of the trace component was greatest with Oakley sand and progressively less with the soils containing larger clay and silt fractions These differences, particularly in the case of Hesperia soil, cannot be attributed to variations in porosity, but are probably due to channeling and microscopic variations in permeability.

(2) Iodine-131 demonstrated a tendency to precede fluorescein but in no instance did recovery exceed 44 pct. The fluorescein curve exhibited a displacement and a trailing elution limb characteristic of strong adsorption. Increasing quantities of clay, silt, and organic matter appear to be related to reduced peak iodine concentrations and lower overall recovery.

(3) Effective porosities calculated from the time of arrival corresponding to $c/c_0 = 0.10$, column lengths, and the volumetric flow rates are: Oakley, 0.35; Yolo, 0.42; and Hesperia, 0.06. In the case of Hesperia soil, tracer velocities based on the $c/c_0 = 0.10$ point are approximately six times the mean velocities given by Darcy's law and the conductive porosity.

(4) The displacement of the iodide and

TABLE 2 – *Characteristics of breakthrough-elution curves*

Item	Volume through-put per column volume								
	Oakley			Yolo			Hesperia		
	Cl^-	I^{131}	Fluor.	Cl^-	I^{131}	Fluor.	Cl^-	I^{131}	Fluor.
Initial arrival	0.32	0.33	0.35	0.38	0.30	0.46	0.05	0.07	0.07
$c/c_0 = 0.1$	0.36	0.43	0.47	0.46	0.61	0.68	0.11	—	0.13
$c/c_0 = 0.5$	0.45	—	0.59	0.57	—	0.92	—	—	—
c/c_0 = max.	0.64	0.64	0.75	0.81	0.85	1.05	0.52	0.52	0.42
Initial Tracer Concentration c_0	153 ppm	2290 cpm/ml	31 ppm	183 ppm	2810 cpm/ml	47 ppm	158 ppm	3090 cpm/ml	28 ppm
Percent Recovery	89	44	138[a]	100	33	170[a]	100	15	130[a]
Rate, liters/min.	5.4	6.3	4.5	1.4	1.2	1.5	0.16	0.20	0.13
Rate ml/min cm^2	0.82	0.96	0.68	0.21	0.18	0.23	0.024	0.030	0.020

[a] Adjusted to 100 pct. in plotting. Increased percentages are attributed to alteration of light transmission characteristics after movement of fluorescein through the soil.

fluorescein curves with respect to that of chloride must be assumed to be caused by a chromatographic separation within the soil column. Due to relatively high velocities and limiting rates of adsorption, the initial times of arrival for these tracers were not delayed but the delayed positions of the peak concentrations are caused by hold-up on the solid phase with subsequent elution. Variations in volumetric flow rates (Table 2) may account for some of the differences evidenced by the break-through elution curves.

The data shown in Figure 5 are of particular value in illustrating the weakness of cationic radioisotopes as water tracers. In a single run the concentration histories of chloride, calcium, and radioactive calcium-45 were determined. Although the sodium-calcium ratio of the traced liquid was matched as nearly as possible to that of the influent water, it is evident that a slight chromatographic separation of calcium from the sodium occurred. This phenomenon suggests that the added stable calcium component was too great and hence a calcium replacement of sodium took place. The sharp break-through and trailing elution curves for calcium are evidence that it is more strongly held than sodium and the resulting equilibrium parameter (r_{Ca}) is less than unity. The most seemingly anomalous result of this run was the early appearance of calcium-45 in the column effluent with a peak concentration at approximately the same time as that of chloride and stable calcium. According to Eq. (1) the calcium-45 break-through front should travel at a rate of approximately 0.01 that of the water. Following the passage of several column volumes of tap water, a core sample of the Yolo soil was removed from the lysimeter. Analysis of one inch increments of the sample for calcium-45 revealed that a major portion, in excess of 80 pct, of the activity remained in the column within three to four inches of the surface. It may be concluded that the break-through elution curve for calcium-45 as shown in Figure 5 was not the true chromatograph but was due to the failure to establish an exchange equilibrium as the tracer front passed through the column. At lower volumetric flow rates the peak calcium-45 concentrations and the extent of initial recovery of this tracer would have been even less than that indicated in Figure 5. It is evident that calcium-45 would not constitute a satisfactory tracer where ground water velocities are low, exchange capacities high, and travel distances relatively great.

Use of the radioisotope of hydrogen, tritium, as a tracer in hydrologic and meteorologic studies has been suggested by *Libby* [1954]. While assay techniques for tritium present a number of special problems, it appears to have some potential as a ground-water tracer. The results of two tracer runs using tritium and chloride simultaneously on Yolo sandy loam are shown in Figure 6. These tests were made on a small column, 1.5 inches in diameter and containing six inches of soil. By adding several pore volumes of traced water it was possible to avoid distortion of the break-through and elution curves.

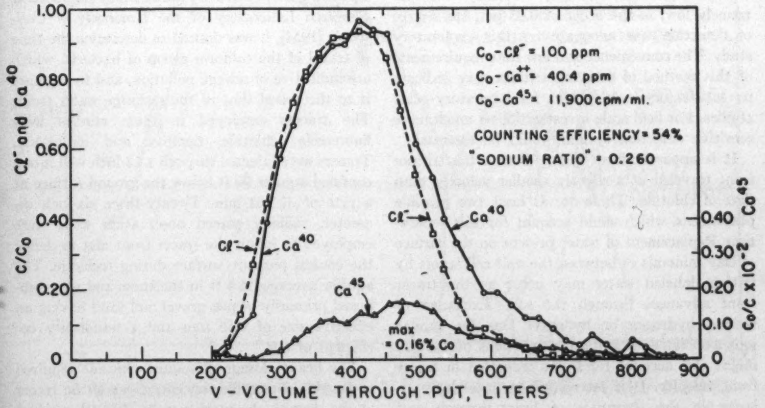


FIG. 5 – Comparison of Ca^{40} and Ca^{45} tracers breakthrough elution curves, Yolo sandy loam

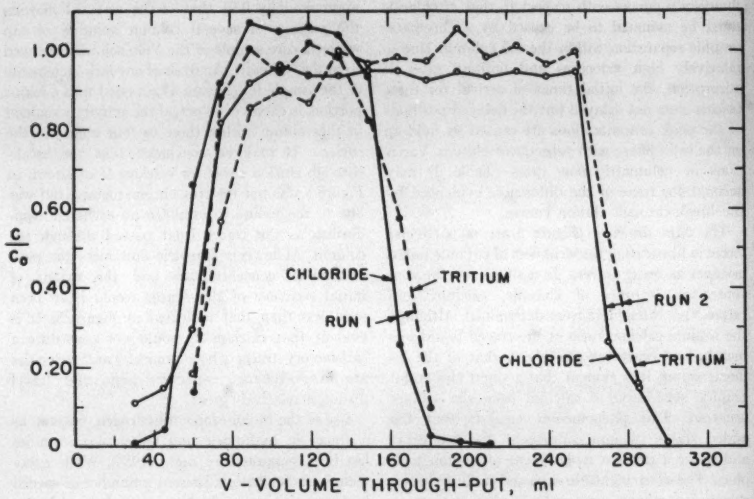


FIG. 6 – A comparison of tritium and chloride tracers, Yolo sandy loam

Tritium was counted as water in 1.75-inch diameter aluminum pans placed in the chamber of a three-inch diameter proportional flow counter operated with methane gas at 4800 volts. By carefully regulating the gas flushing rate at 75 ml per minute the variance in radio-assays was held within a factor of two of that expected from statistical theory. Although counting efficiency was extremely low, in the order of 0.05 pct, the degree of detection was adequate for this exploratory study. The convenience and low time requirements of this method of assaying tritium may indicate its satisfactory employment for laboratory scale studies. For field scale investigations a much more sensitive detection system would be essential.

It is apparent from Figure 6 that the tritium front traveled at a slightly smaller velocity than that of chloride. There are at least two possible phenomena which could account for this separation. Replacement of water present on the surface of clay minerals or between the unit cell layers by tritium labeled water may occur as the tracer front advances through the soil. Exchange of labeled hydrogen or hydroxyl ions for similar ions associated with the clay portions of the soil might also account for slight reduction in tracer front velocity. It is interesting to note the similarity in the sharpness of break-through and elution curves for tritium and chlorides, an indication of rapid tritium interchange between liquid and solid phases. Such exchange reactions would probably be of small consequence in the passage of natural tritium through aquifers since equilibrium would be maintained by the continuous supply of tritium at points of aquifer recharge.

Field studies—During the course of an investigation of pollution travel by the Sanitary Engineering Research Laboratory of the *University of California* [1954], it was desired to determine the time of travel of the coliform group of bacteria, which are indicative of sewage pollution, and to compare it to the travel time of the recharge water front. The tracers employed in these studies were fluorescein, chloride, dextrose and iodine-131. Tracers were injected through a 12-inch well into a confined aquifer 90 ft below the ground surface at a rate of 37 gal/min. Twenty-three six-inch diameter, radially placed observation wells were employed to follow the tracer front and to define the conical pressure surface during recharge. The aquifer averaged 4.4 ft in thickness and was composed primarily of pea gravel and sand having an effective size of 0.56 mm and a uniformity coefficient of 6.9.

The heavy dosage of sodium chloride required to provide detectable concentrations of the tracer at the distant observation wells (500 ft) resulted in density separation of the tracer in the vicinity

TABLE 3 – *Comparative travel times of various tracers during injection well operation*

Distance from injection well	Time of arrival of first detectable tracer				
	Computed[a]	I^{131}	Coliform organisms	Dextrose	Fluorescein
ft	*hr*	*hr*	*hr*	*hr*	*hr*
13	2.8	1.1	0.4	0.6	0.2
63	65	29	23	8.2	2.8
100	160	75	24	16	15

[a] Computed mean time of front arrival based on an injection rate of 37 gpm into a confined aquifer having an average thickness of 4.4 ft and a porosity of 0.35.

of the injection well and the sporadic arrival of the tracer at the points of observation. Fluorescein tracer was introduced into the aquifer by the injection of 450 gal of a 100-ppm solution of sodium fluorescein. Twenty pounds of sugar at a concentration of 6000 ppm were introduced in a similar manner. Twenty millicuries of radio-iodine were introduced over a three-minute period at the normal injection rate. Coliform organisms originated from the continuous injection of a mixture of ten per cent settled sewage and recharge water. A summary of arrival times at three observation wells situated along the southerly meridian through the injection well is shown in Table 3. Results of the iodine-131 run are given in Figure 7 for the same three wells.

It is apparent from Table 3 that all of the tracer fronts show extreme fingering and that the maximum rates of recharge water travel greatly exceed the average calculated from an assumption of a homogeneous aquifer. Iodine was the least satisfactory tracer if evaluated in terms of its time of arrival in comparison with dextrose and fluorescein. In order to detect the relatively small concentrations of radioiodine arriving at the 63-foot and 100-foot wells, it was necessary to evaporate 20 ml samples and to perform the assay for beta radiation with the internal flow counter previously described. At a distance of 100 feet from the recharge well, iodine activities did not exceed 6.5 counts per minute per ml, or 6 $\mu\mu c$/ml, and were extremely erratic. The fluorescein tracer reached the 100-foot well at a peak concentration of 0.4 ppm and exhibited a trailing elution limb similar to that observed with the lysimeters.

Discussion and conclusions—It is evident that none of the tracers studied is completely satisfactory for every situation. Each tracer has its limitations and should not be used without a full appreciation of the conditions imposed by both the carrying liquid and the medium through which it

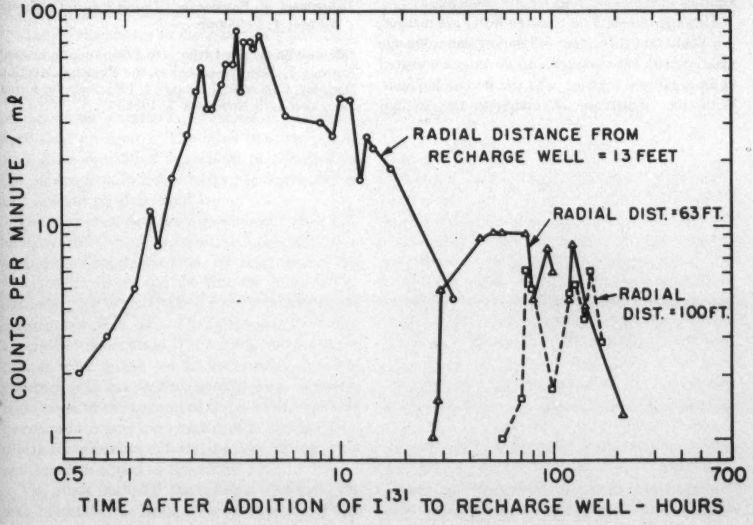


FIG. 7 – Travel of I^{131} in confined aquifer

must pass. Radioisotopes employed in cationic form will probably be unsatisfactory in any situation involving porous media with a measurable exchange capacity. Similarly, anionic radio elements when used in a carrier-free form will be largely retained by adsorption. The addition of carrier to anionic radioisotopes may not eliminate exchange losses unless the carrier concentration is large when compared to the carrier associated with the solid phase. There is some evidence that iodine-131, in the presence of several parts per million of carrier iodide, will pass through several feet of soil without significant retardation. Retardation of fluorescein as noted in these investigations has been reported in the literature [*Plummer*, 1945; *Sturm* and *Johnson*, 1950; *Heck*, 1954; *Watkins* and *Mardock*, 1945]. Dextrose has been reported as behaving satisfactorily as a tracer, although in these studies (Fig. 3), it was observed to move at a lower rate than chloride. The susceptibility of dextrose to decomposition by soil micro-organisms seriously limits its use as a ground-water tracer. Under the conditions imposed by the lysimeter studies, the chloride ion was the most satisfactory indicator of water movement. However, cognizance must be taken of density effects if high chloride concentrations are employed and the danger of altering the permeabilities of high-clay soils by ion exchange.

Although the data on tritiated water are meager, it is likely that this tracer will undergo an exchange reaction with the various forms of water associated in an organized manner with the porous medium. With the occurrence of exchange the tritium tracer will fail to correctly depict the ground water velocity.

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Forest-Cover Effects on Snowpack Accumulation and Melt, Central Sierra Snow Laboratory

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Abstract—Snowpack accumulation and melt at measurement points within snow courses were related to two forest-cover variables. Water equivalent of the snowpack on April 1 of each year and melt rate after April 1 per unit of degree-days above 35° F were studied. Cover variables were the amount of shade from trees to the south of a snow measurement point and the amount of shielding from trees to the north of the point. The amount of shade was expressed as the duration of shading between April 1 and June 15, multiplied by the amount of direct solar energy which would have struck the snow surface in the absence of shading. Shielding was expressed by the ratio of average tree height to distance of the trees from the measurement point. Data from five points in each of five snow courses for three years of record were analyzed by the method of covariance. The analyses showed a high degree of association between the snowpack and forest-cover variables. The results are interpreted in terms of the timber-cutting pattern that would result in maximum accumulation of snow, minimum melt rate, and maximum prolonged release of snow water in the spring.

Introduction

The Sierra-Cascade snowpack of each year is a principal source of water supply for much of central California [*Strauss*, 1954]. An estimated 38 pct of the total streamflow of the state comes from the mountain areas where deep snowpacks and commercial forests are coexistent [*Colman*, 1955]. Since the forests in the snowpack area are subject to harvesting, can the harvesting be done in ways that will improve water yield?

Clues to the answer to this question were sought by a study of the relation of the snowpack to forest cover conditions. Two snowpack characteristics were studied. One was the maximum accumulation of the winter snowpack, expressed as the water equivalent on April 1. The other was the rate of melt (here considered equivalent to ablation) of the snowpack in inches of water per degree-day of air temperature after April 1.

The snowpack data used in the study were collected at the Central Sierra Snow Laboratory as a part of the Cooperative Snow Investigations of the Corps of Engineers and the Weather Bureau. The data analyzed were obtained from five snow measurement points in each of five snow courses during a period of three years (1949–1951). All five snow courses were in the red fir forest type. The five points in each course were selected so as to have a wide range in the amount of forest cover. Air temperature data were from nearby Soda Springs. Two physical expressions of forest cover conditions were developed as a part of this study.

The study included three steps. The first step was to obtain the basic data for analysis. There were three tasks to do in this step: (a) selecting an expression of degree-days of air temperature which was proportional to snow melt in the spring; (b) determining the water equivalent of the snowpack on April 1 and the average melt rate after April 1; and (c) developing physical expressions of forest cover and calculating their magnitudes at the individual snow measurement points. The second step was to analyze the snowpack and forest cover data to determine the relation of forest-cover expressions to the April 1 snowpack and to the melt rate. The third step was to apply the relations; that is, to estimate how cutting a forest in various patterns would affect snow accumulation, melt rates, and resultant average amounts of unmelted snow at various dates in the spring.

Obtaining the Basic Data

Selecting a degree-day expression—Preliminary studies of the melt of the snowpack in the spring showed wide variations in the average melt per day for successive periods in a year, and from year to year. Using some unit of degree-days of air temperature in expressing melt rates promised to remove some of this variability. Several expressions of degree-days were tried. Degree-days above 32°F (calculated as the average of maximum and minimum daily temperatures) was found to be fairly well related to melt. This relation was not improved by including the independent effect of freezing days; that is, degree-days below 32°F. However, there was an indication that the relation of melt to degree-days above 32°F was not linear. When degree-days above 35°F was used, the relation to melt was found to be linear (Fig. 1). Hence, degree-days above 35°F was chosen as the unit to be

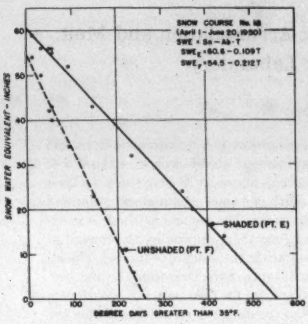
SNOW COURSE No. 18
(April 1 - June 20, 1950)
SWE = Sn - Ab · T
SWE = 60.6 - 0.109 T
SWE = 54.5 - 0.212 T
SNOW WATER EQUIVALENT - INCHES
SHADED (PT. E)
UNSHADED (PT. F)
DEGREE DAYS GREATER THAN 35°F.

FIG. 1 – Relation of snow water equivalent, after April 1 to degree-days of air temperature for two points, Snow Course 18, Central Sierra Snow Laboratory, 1950.

used to express snow melt rate. This unit has been found useful by *Church* [1941]. For the analyses that were made, inclusion of snowfall after April 1 as a variable did not significantly improve the estimation of melt. The reason for the nonsignificance may be that only small quantities of snow fell after April 1.

Determining April 1 snowpack and average melt rate—Since the snowpack was seldom measured on April 1 of each year at every snow measurement point, the April 1 snowpack was an extrapolated value. Extrapolations were made from the periodic measurements of the pack after April 1. The average melt rate was also obtained from the periodic measurements of the snowpack after April 1. Both the average melt rate and the extrapolated April 1 snow water equivalent were obtained in one step by least-squares solution of

$$SWE = Sn - Ab \cdot T \qquad (1)$$

where SWE was one of the periodic measurements of the snow water equivalent at a snow measurement point, in inches; Sn is the extrapolated April 1 snowpack in inches water equivalent; Ab is the average melt rate in inches per degree-day above 35°F; and T is the degree-days above 35°F cumulated from April 1 to and including the date of the snow measurement. The daily value of T was the average of the daily maximum and minimum temperatures measured at Soda Springs, less 35°F, corrected for elevation by subtracting 3°F per 1000-foot increase in elevation of the snow measurement point above Soda Springs [*Miller*, 1955, p. 18].

The number of periodic snow measurements used in each solution of (1) ranged from 4 to 13. Data and solutions for two points are illustrated in Figure 1. For all 75 solutions, the April 1 snowpack ranged from 20 to 82 inches water equivalent, and the melt rate ranged from 0.063 to 0.255 inches water equivalent per degree-day above 35°F (Table 1).

Determination of the degree to which these wide variations were associated with differences in forest cover required that indexes be devised of the physical effects of the forest cover at each snow measurement point.

Developing physical expressions of the forest cover—Forest cover was characterized around each snow-measurement point separately for trees north

TABLE 1 – *Extrapolated April 1 snowpack water equivalent and average melt rate after April 1 for various snow measurement points, with associated forest shade and height-to-distance ratios*

Course and point[a]	April 1 snowpack, Sn			Melt rate, Ab			Shade Sh	Height/distance h/d
	1949	1950	1951	1949	1950	1951		
	inches, water equiv.			inches/°day above 35°F			pct	ft/ft
10 A	48	68	43	0.201	0.140	0.117	0	0
B	45	66	39	0.183	0.142	0.106	0	0.1
E	48	67	37	0.197	0.141	0.063	0	0.5
C	56	76	47	0.180	0.159	0.124	5	0
D	48	73	52	0.160	0.136	0.102	52	0
18 D	32	54	41	0.198	0.169	0.138	14[b]	0.9
F	32	54	39	0.255	0.212	0.162	8[b]	0.7
B	38	57	47	0.136	0.106	0.102	34[b]	4.4
H	41	58	38	0.142	0.100	0.090	79[b]	0.8
E	38	61	47	0.124	0.109	0.086	44[b]	1.7
19 B	32	43	20	0.148	0.166	0.090	20	6.2
A	40	55	26	0.169	0.172	0.100	62	1.5
E	41	57	30	0.144	0.175	0.105	83	1.7
C	38	58	26	0.123	0.164	0.090	90	2.0
D	42	48	26	0.116	0.094	0.087	100	5.7
21 A	46	71	51	0.209	0.156	0.136	0	0
B	42	64	40	0.172	0.116	0.121	1	0.2
F	45	68	48	0.199	0.170	0.130	2	0
D	49	74	56	0.185	0.133	0.111	25	0.1
C	48	70	53	0.183	0.128	0.116	47	0.2
22 B	44	74	46	0.152	0.135	0.111	7	0.2
H	49	76	50	0.162	0.133	0.111	13	0.4
D	57	82	52	0.106	0.105	0.065	66	0.3
G	45	76	46	0.107	0.123	0.079	80	1.5
F	37	58	34	0.092	0.079	0.080	100	16.8

[a] Source: [*Central Sierra Snow Laboratory*, 1952].

[b] An error in the map for Snow Course 18 was reported by one of the reviewers, so the values of the shade (Sh) at this course were redetermined in the field.

of the point and south of the point. This separation was made because the forest cover on the two sides was expected to have different effects on snow accumulation and melt.

The effects of trees to the south were indexed by the shade they produced. Shade was expressed for each measurement point as the percentage duration of shade during various daylight hours (represented by azimuth segments) in the period April 1 to June 15 (Table 2) weighted by the percentage of direct solar energy during those hours (Table 3). The data used in the calculation were: The average height of the tree tops above the snow-measurement point; the horizontal distance from the edge of the tree canopy to the point, determined from maps [*Central Sierra Snow Laboratory*, 1952]; and the solar energy as of May 12 (the mid-date of snow melt in the open), by azimuth segments for the particular slope and aspect at the snow-measurement point. Solar equations given by *Byram* and *Jemison* [1943] were used. (Tabular solution of these equations giving the intensity of solar radiation, sin θ, at latitude 34° for hour angles by 30° intervals, slopes by ten percent intervals to 100 pct, and azimuths by 45° intervals, were compiled several years ago under the direction of W. L. Fons, California Forest and Range Experiment Station, Berkeley, California. These greatly facilitated the calculations.) The index of shade (Sh) for each snow-measurement point is given in Table 1.

The effects of trees to the north of the snow-measurement point were indexed by the ratio of the tree height to tree distance, h/d. Trees to the north were expected to reduce winter snow accumulation by radiating heat to the pack. This radiating effect would also tend to increase the spring melt rate, but the effect would be offset by other effects such as the interception of diffuse sky radiation, retardation of air movement near the snow surface, and maintenance of snow conditions which cause high reflection from snow. The h/d ratio was termed the shielding index. In determining this index the values used were the average height of the tree tops above the snow and the horizontal distance from the edge of the tree canopy to the snow-measurement point. Trees at distances greater than three times tree height were ignored. The shielding index for each snow-measurement point is given in Table 1.

TABLE 2 – *Per cent of daylight hours, April 1 to June 15, in which trees south of snow-measurement point shade the snow, by azimuth segment*

Ratio of height to distance[a]	Azimuth 90°–135° and 225°–270°	Azimuth 135°–225°
	pct	pct
0.35	0	0
0.40	11	0
0.50	40	0
0.60	85	0
1.10	100	0
1.40	100	21
1.70	100	46
1.90	100	63
2.10	100	89
2.20	100	100

[a] Height of tree tops above the snow measurement point divided by horizontal distance from edge of tree canopy to the point.

TABLE 3 – *Relative solar energy by azimuth segments for various aspects and slopes, May 12, latitude 39°20′ N*

Aspect and slope[a]	Azimuth <135°	Azimuth 135°–225°	Azimuth >225°
	pct	pct	pct
Level	14.2	71.6	14.2
N, 20	15.1	69.8	15.1
N, 50	16.5	67.0	16.5
NE, 20	19.4	70.3	10.3
NE, 50	27.1	67.7	5.2
E, 20	20.2	71.2	8.6
E, 50	27.2	69.9	2.9
SE, 20	18.4	71.5	10.1
SE, 50	22.5	71.7	5.8
S, 20	13.7	72.6	13.7
S, 50	13.5	73.0	13.5

[a] For example, N, 20 is north aspect 20 per cent slope (accuracy to one per cent only). NW and SW slopes taken to be same as NE and SE respectively.

Analysis of the Snowpack and Forest Cover Data

The relation of the April 1 snowpack and the average melt rate to forest shade and shielding were determined by covariance analysis of the data of Table 1. The 75 values of the April 1 snowpack (Sn) and the average melt rate (Ab) were analyzed separately, using the two forest variables as the covariants. The within-course-and-year relationships were the ones sought, for two reasons: Between-course variation in the April 1 snowpack varies widely because of terrain differences between courses [*Mixsell* and others, 1953]. Between-year variation is high in both the April 1 snowpack and the spring melt rates, varying with snow conditions as produced by the weather peculiar to the previous winter [*Miller*, 1955, p. 137]. These sources of variation were eliminated by analyzing the within-course-and-year relations between forest cover and snow.

Effect of forest cover on the April 1 snowpack—The average relation of the April 1 snowpack (Sn) in inches water equivalent, to forest shade (Sh) and shielding (h/d) is given by the within-course-and-year equation obtained from the analysis of covariance

$$Sn = 47.7 + 0.216\ Sh - 0.00167\ Sh^2 - 0.924\ h/d \quad (2)$$

with the standard error of estimate being 3.6 inches water equivalent. No differences in the regression coefficients were detected between years, so this equation was used for all years. All three regression coefficients in the equation are significant at the one per cent level. The equation indicates that variation in the forest-cover indexes explains 56 pct of the variation in the snowpack water equivalent between the individual snow-measurement points within courses and years. It also shows that the relation of April 1 snowpack to shade is curvilinear with a maximum pack obtained at a point where shade is 65 pct and there are no trees to the north. On the average, the April 1 snowpack contained 11 inches less water in a dense forest (Sh = 100, h/d = 16.8) than in large open areas (Sh = 0, h/d = 0).

Field observations indicate that differences in April 1 snowpack expressed by (2) may represent the net effect of three factors: differences in winter melt, loss by interception, and blowing of snow by the wind. That differences in winter melt exist is indicated by Snow Laboratory notes that soil was wet under snow in the forest when soil was dry in the open, and by a Laboratory note on February 5, 1951, that "melting snow dripped from trees like a heavy rain." Interception loss can be estimated from a study by *Rowe* and *Hendrix* [1951] in a pine stand at a lower elevation in the Sierra Nevada. During snow storms an average of 8.6 pct of the precipitation was retained on the tree crowns and evaporated from them. If the same percent loss held at the Laboratory, interception loss would amount to 4 to 5 inches on the average. Thus interception loss accounts for less than half of the 11-inch difference between April 1 snowpacks in the dense forest and in large open areas. Additional study of the relation of forest cover to the physics of snowpack accumulation is needed before this difference can be explained.

Since the April 1 snowpack increased with shading and decreased with shielding, the relative magnitudes of these two effects were determined. Eq. (2) was solved for a systematic sample of points in a forest opening large enough that the full range of Sh and h/d was represented; thus the total effect of both was obtained. The result indicated that shade from trees to the south was about two times as effective in increasing the April 1 snowpack as radiation from trees to the north was in reducing the pack.

Effect of forest cover on the average melt rate—The relation of melt rate in inches per degree-day above 35° F (Ab) to forest shade (Sh) and shielding (h/d) is given by the within-course-and-year regression equation

$$Ab = 0.160 - 0.00089\ Sh + 0.0000043\ Sh^2 - 0.00183\ h/d \quad (3)$$

with the standard error of estimate being 0.022 inches per degree day. No differences in the regression coefficients were detected between courses and years. The regression coefficient for forest shade is significant at the one per cent level, and that for shielding at about the five per cent level. A possible substitute for the shade variable, the height-to-distance ratio of trees to the south, was tested but found to be much poorer than the shade variable used, explaining 36 pct less of the variance.

The analysis indicated that 40 pct of the variance of melt rates within courses and years is explained by differences in the forest cover variables. Eq. (3) indicates that melt rate decreases progressively with shielding and with shade, with 50 pct shade being three-fourths as effective as full shade. The equation indicates that the melt rate in a dense forest (Sh = 100, h/d = 16.8) would be about 53 pct of that in a large unshaded area (Sh = 0, h/d = 0).

This equation also was solved for a sample of points in an opening large enough to include the full range of Sh and h/d. The result indicated that shielding by trees to the north was about 12 pct as effective in decreasing melt rate as was shade from trees to the south. This is about the proportion of sky radiation to total solar radiation.

Effect of forest cover on residual snowpack—The amount of water held in the snowpack on several dates after April 1 was estimated under various conditions of forest cover. To make the estimates most useful they were based on the long-term average April 1 snowpack and the long-term average degree-days in the spring. The long-term average snowpack on April 1 at open courses at and near the Laboratory has been estimated by the *California Division of Water Resources* [1954, p. B 9]. The snowpack for the years in the present study (1949–1951) was 83.3 pct of the long-term average. Therefore, the constant 47.7 in (2) was divided by 0.833 to give a new constant, 57.3, applicable to the long-term average snowpack. Then, substituting (2)

and (3) in (1) gave

$$SWE = 57.3 + 0.216\ Sh - 0.00167\ Sh^2 - 0.924 h/d - T\ (0.160 - 0.00089\ Sh + 0.0000043\ Sh^2 - 0.00183\ h/d) \quad (4)$$

The amount of water held in the snowpack on any date in the average year, under specific forest conditions, was obtained by substituting in (4). The forest condition was represented by the variables for shade and shielding; the date in the spring was represented by the average total degree-days (T) from April 1 to that date. The average, long-term values of (T) at elevation 7600 feet were estimated from data of *U. S. Weather Bureau* [1954] as: 50 on May 1, 130 on May 15, 270 on June 1, 360 on June 9, 435 on June 15, and 670 on July 1.

In this way the seasonal change of the snowpack in a large unshaded area (Sh = 0, h/d = 0) was compared with that in a dense forest (Sh = 100, h/d = 16.8), with the following results: On April 1 the unshaded area held 11 inches more snow water. On May 1 the difference had dropped to seven inches. By June 1 the relation had reversed, the dense forest having ten inches more snow water than the unshaded area. On June 9, when the snow had disappeared from the unshaded area, 16 inches of snow water remained in the dense forest.

For a year of very light snowpack, as in 1951, it was estimated the dense forest would have seven inches of water left as snow when the unshaded area was bare. For a year of very heavy snowpack, as in 1952, the dense forest would have some 36 inches water stored as snow when the unshaded area was bare.

Effect on the Snowpack Produced by Cutting the Forest

The effects of cutting the forest in certain patterns were estimated from (2), (3), and (4). For these estimates, the shade and the shielding were determined point by point, for points spaced at one-tenth tree height within hypothetical openings cut in the forest. The resultant values of Sh and h/d were substituted in the equations and the average of the point solutions gave the areal average. Thus, the April 1 snowpack, the average melt rate, and the amount of unmelted snow associated with any value of degree-days and date were obtained.

Strip-cutting—For strips of various widths cut in an east-west direction through a level forest, Figure 2 shows that the maximum April 1 snowpack occurs when the strip is about nine-tenths as wide as tree height. However, snow melt after April 1 is more rapid in wide than in narrow strips; as the spring season progresses the maximum unmelted snow is found in narrower and narrower strips. By June 9 the maximum snow water equivalent is found in strips half as wide as tree height.

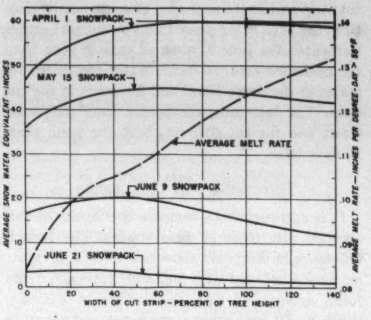
APRIL 1 SNOWPACK
MAY 15 SNOWPACK
AVERAGE MELT RATE
JUNE 9 SNOWPACK
JUNE 21 SNOWPACK
AVERAGE SNOW WATER EQUIVALENT - INCHES
AVERAGE MELT RATE - INCHES PER DEGREE-DAY > 32°F
WIDTH OF CUT STRIP - PERCENT OF TREE HEIGHT

FIG. 2 – Snowpack water equivalent on various dates in an average year within strips of various widths cut in a forest

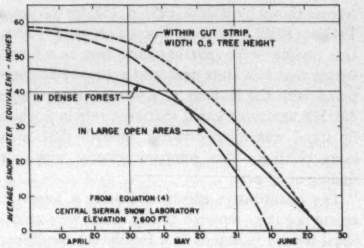

FIG. 3 – Snowpack water equivalent at various dates in an average year for two forest conditions and in the open

Block-cutting—The effect on snow of cutting a forest in blocks of two shapes was compared with the effect of cutting east-west strips one tree height wide. For a square block one tree height across, the snow water equivalent on June 9 would be about three inches more than in the strip. For a rectangular block five tree heights long by one tree height wide, with the long dimension oriented east and west, the snow water on June 9 would be only about one-half inch greater than in the strip.

Three conditions compared—Water in the snowpack on various dates after April 1 of the average year is shown in Figure 3 for three conditions: A pack in a large unshaded area, a pack in a dense forest, and a pack within an east-west cut strip half as wide as the heights of the adjacent trees. On April 1 the snowpack water equivalent in the

cut strip and in the unshaded area are nearly identical, the pack in the dense forest contains 11 inches less water. On June 9, when all snow is gone from the unshaded area, 16 inches water equivalent remains in the dense forest and 20 inches in the cut strip. The last snow disappears from the dense forest and the cut strip at about the same time, 16 days later.

Discussion and Conclusions

It is appropriate to compare the results of this analysis with those of other studies. The 11-inch difference in maximum snowpack water equivalent on April 1 between large unshaded areas and dense forest agrees well with the findings of *Kittredge* [1953, p. 31] for similar cover types and years. It agrees well, too, with a 12.7-inch difference reported by *Mixsell* and others [1953, App. Table 2] for the single year 1950, and with a nine-inch average difference shown by *Wilson* [1954, p. 188] for the years 1947 to 1950, both from Snow Laboratory data. Our finding of the average melt rate in a forest versus that in a large unshaded area may be compared with the findings of *Kittredge* [1954, Table 30]. His analysis showed that melt rate in a white fir stand was approximately one-half that in a large clearing. This compares closely with our finding of 53 pct.

The quantitative effects of cutting a forest to create openings reported in this study were calculated for red fir stands in a freshly cut condition, and the effects would presumably diminish in succeeding decades as the forest became re-established. The quantitative effect for a whole forested area would depend also on the species cut, on the percentage of the forest which was cut, and on the pattern and sequences of the cuts.

It is concluded that management of the forest in the snowpack zone can have important effects on snow accumulation, melt rate, and the timing of snow-water runoff in the spring. The study indicates that accumulation of the snowpack can be maximized by cutting the forest so as to retain the most shade while reducing the height of trees to the north. This can be accomplished by harvesting a forest in successive narrow strips, oriented normal to the direction of maximum solar radiation, with the successive strips proceeding southward. Such cutting will produce a 'wall-and-step' forest, with the wall being generally toward the south and the steps toward the north. On the other hand, spring melt rate can be minimized by maintaining the maximum possible tree canopy. However, under a dense canopy maximum accumulation is less than in openings within a forest. Therefore, snow-water runoff can be prolonged most by making openings with a width equal to about half the height of the trees.

These conclusions should be considered primarily as hypotheses worth testing. Research is now under way to refine these hypotheses and to evaluate snowpack management quantitatively in terms of its effect upon water yield.

Acknowledgments

The excellent data collected as part of the Cooperative Snow Investigations of the Corps of Engineers and the Weather Bureau made this study possible. The author wishes to acknowledge the encouragement and help of E. A. Colman in the study.

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Geological Application of Extreme-Value Methods to Interpretation of Cobbles and Boulders in Gravel Deposits

W. C. Krumbein and Julius Lieblein

Abstract—Unusually large cobbles or boulders are sometimes observed in gravel deposits. Their occurrence raises the question whether individuals of such size may be considered as part of the pebble population or as 'erratics' transported by ice or other means. Large cobbles or boulders normally present in fluvial gravels presumably are related to competence of the transporting stream. This paper presents data on Brandywine (Pliocene?) gravel in Maryland, believed to be of fluvial origin. The largest cobbles in subsamples of fixed size were measured and arranged into an extreme-value distribution. Extreme-value theory provides a basis for estimating the likelihood of occurrence of large individuals in a given group. The fit is satisfactory in terms of conventional limits, and leads to the belief that all large particles observed in the deposit are normal members of the stream-pebble population. The study therefore suggests that extreme-value methods may be applicable to other sedimentary problems. Some necessary mathematical details of the theory for such applications are given in the Appendix.

Introduction—Extreme-value theory has found wide application in a number of geophysical fields, including hydrology, meteorology, and oceanography [*Gumbel*, 1941, 1954; *Court*, 1952; *Longuet-Higgins*, 1952; *Gumbel* and *Lieblein*, 1954]. The theory is concerned with the probability of occurrence of extreme events, such as large floods, or of extreme individuals in a group. This paper is a preliminary study to explore possible applications to size of particles in sedimentary deposits.

Gravel deposits commonly display a wide range of particle sizes, and it is not unusual to find cobbles or boulders noticeably larger than the average in pits or natural exposures of fluvial gravel. Such large boulders have been interpreted by some as 'erratics' transported to the site by extraneous agents. When a single very large boulder is found embedded in pebbles with no evidence of intermediate sizes present, the inference that an extraneous agent has operated is probably justified. In Pleistocene alluvial deposits especially, such large individuals are commonly considered to represent objects rafted by ice from some point nearer the glacier where large boulders may be numerous. When scattered cobbles or boulders occur, it becomes a matter of judgment whether to consider the largest particles as erratics or as part of the local deposit.

It is believed that extreme-value theory may be helpful in deciding which of the preceding alternatives is more likely. If the largest objects show a reasonable probability of belonging to the distribution of extreme individuals normally associated with the local deposits, it would seem unnecessary to call upon extraneous processes to account for their occurrence in the deposit.

Method used in the present study—Brandywine gravel of Pliocene (?) age occurs as an extensive though partially eroded sheet on the upland in Maryland between the Anacostia River and Chesapeake Bay, southeast of Washington [*Hack*, 1955]. The gravel is relatively coarse in its northwestern part, and decreases in average particle size toward the southeast and south (personal communication from John Schlee, John Hopkins University). A large gravel pit at Gordon's Corners was selected for study. The pit afforded excellent fresh exposures of the relatively coarse phase of the gravel. A 12-ft face about 500 ft long with very recent talus was considered eminently suitable for this preliminary study.

The gravel in the pit is fairly well bedded, with no strongly contrasting textures in the exposed beds. The deposit is a sandy gravel, locally with some clay matrix, and having an average particle size of about 16 mm. The particle size distribution is polymodal and suggests a mixture of several approximately log-normal distributions. It was decided to conduct two sampling experiments, first to determine whether the extreme value theory applied to such deposits, and secondly to observe the change in extreme particle size associated with increasing subsample size.

The first experiment was conducted along the base of the talus slope on the recently excavated face. When such a face yields, the largest particles tend to roll to the toe of the slope. A point along the toe was selected at random and the largest cobble within a small unit area at a systematic interval of two paces was picked up and measured, until a sample of 50 was collected. The length of the intermediate cobble axis was used as an opera-

tionally defined measure of size. This is a conventional practice in sedimentary studies.

It was estimated from the height of the face, and from the number of pebbles exposed per linear foot of uncaved gravel, that each of the larger cobbles came from a subsample having on the order of 25,000 pebbles. These large subsamples were supplemented with 50 smaller subsamples excavated from the undisturbed vertical gravel face just above the talus slope. A volume of gravel estimated to represent 2000 pebbles was excavated at each of 50 sampling points spaced five feet apart along the gravel face. The largest cobble in each of these subsamples was collected and its intermediate diameter measured. As will be seen later, the larger subsample size was overestimated, but the field estimates will be used in the text for convenience.

The term 'subsample' is used here to denote a large set of pebbles from which the largest one is taken. A group of 50 such subsamples then produces a sample of 50 largest values. This use of subsample differs from its common use in statistics, where a subsample denotes a portion of a main sample.

Figure 1 shows histograms of the two samples of 50 largest cobbles. As may be expected, the larger subsamples contain some larger cobbles than the small subsamples, because of the greater probability of including large individuals as subsample size increases. Both histograms show a tendency toward developing a tail to the right, characteristic of extreme-value distributions. The arithmetic mean diameters of the two distributions, computed from the grouped data, are 7.92 cm for the subsamples of 2000 and 10.1 cm for the subsamples of 25,000. On the average, therefore, the larger subsamples picked up cobbles about 2.2 cm larger than did the smaller subsamples.

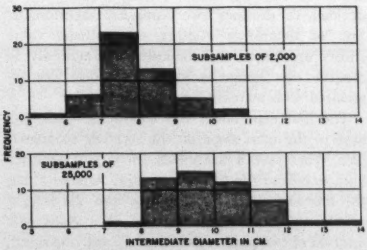

FIG. 1 – Histograms for the largest cobbles in 50 subsamples of 2000 and of 25,000 pebbles

Statistical analysis of the data—The histograms of the raw data are not satisfactory for complete analysis of the distributions, but they serve to indicate the general nature of the raw observations. In further statistical analysis it is more satisfactory to plot the cumulated data on extreme-value probability paper. A straight line of best fit may then be drawn through the points, and a confidence belt constructed as a test of satisfactory fit.

In preparing the data for plotting, the measurements in each sample are ranked cumulatively in order of size from 1 to 50, as shown in Table 1. The rank number, i, is divided by 51 according to the formula $P = i/(n + 1)$, [*Kimball*, 1947; *Gumbel*, 1954], where $n = 50$ is the sample size. The resulting values, also shown in Table 1, are plotted on the frequency scale against the observed diameter of the cobble. Use of $(n + 1)$ instead of n permits plotting all 50 points on the graph.

Figure 2 shows the sample data on extreme-value probability paper. The fit is satisfactory for all practical purposes and the graphs may be used to note several features. These are indicated mainly for geologists who may not be familiar with the implications of extreme-value graphs.

The most evident feature of the curves is that the sample points lie along approximately parallel fitted lines. This is predicted by extreme-value theory according to which extremes of large subsamples tend to lie a constant distance from extremes of smaller subsamples taken from the same population. This constant distance is governed by a simple relationship involving the ratio of large to small subsample size.

Charts such as Figure 2 can be used not only for verifying extreme-value theory, but also to make predictions and estimates. For example, the chance that an extreme pebble from a subsample of 2000 will exceed 10 cm in intermediate diameter is read from the frequency scale as $1.000 - 0.930 = 0.070$. This is one pebble in 14 such extremes, on the average. The value 14 can also be read from the right-hand scale for return period. The corresponding probability that an extreme from a subsample of 25,000 pebbles will exceed 10 cm is considerably more, as would be expected. From the frequency scale this probability is $1.000 - 0.575 = 0.425$, an average of one in 2.3, which may also be checked on the return period scale.

Another question that may be asked of Figure 2 is how often, on the average, would one find a cobble as large as the largest in each of the two

TABLE 1 – *Cumulated frequency and plotting values for subsamples of 2000 and 25,000 pebbles*

Intermediate diameter (x_i)	Subsamples of 2000		Subsamples of 25,000	
	Cumulated frequency (ranked value, i)	Plotting value $i/(n+1)$	Cumulated frequency (ranked value, i)	Plotting value $i/(n+1)$
cm				
5.8	1	0.020	...	...
6.0	3	0.059	...	...
6.2	4	0.078	...	...
6.4	4	0.078	...	...
6.6	6	0.118	...	...
6.8	6	0.118	...	...
7.0	7	0.137	...	...
7.2	13	0.255	...	...
7.4	15	0.294	...	...
7.6	18	0.353	...	...
7.8	24	0.471	1	0.020
8.0	30	0.588	3	0.059
8.2	35	0.686	3	0.059
8.4	37	0.725	7	0.137
8.6	42	0.823	10	0.196
8.8	42	0.823	12	0.235
9.0	43	0.843	14	0.274
9.2	44	0.863	17	0.333
9.4	44	0.863	19	0.372
9.6	45	0.882	23	0.451
9.8	46	0.902	27	0.529
10.0	48	0.941	29	0.569
10.2	49	0.961	33	0.647
10.4	49	0.961	34	0.667
10.6	50	0.980	34	0.667
10.8	...	...	38	0.745
11.0	...	...	41	0.804
11.2	...	...	41	0.804
11.4	...	...	44	0.863
11.6	...	...	45	0.882
11.8	...	...	47	0.922
12.0	...	...	48	0.941
12.2	...	...	48	0.941
12.4	...	...	48	0.941
12.6	...	...	49	0.961
12.8	...	...	49	0.961
13.0	...	...	49	0.961
13.2	...	...	49	0.961
13.4	...	...	50	0.980

main groups? The T scale gives the answer, which is the same for each group: once in $T = 50$ times, on the average. This last qualification needs emphasis, inasmuch as the statement means that in a large number of cases the number of occurrences will tend to *average* about one in fifty.

The above examples suggest ways in which extreme-value techniques may be useful in geological studies of the kind described here. They are typical of the many relationships that characterize extreme-value procedures. The theory may also be applied to smallest values with only small changes. An exposition of the theory involved in the preceding examples is given in the Appendix below. An understanding of these basic points facilitates application of the method to similar problems in geology.

Geological interpretation of the data—The satisfactory agreement between the observed data and the two extreme-value distributions shown in Figure 2 implies that the cobbles observed in the pit are a normal part of the local alluvial deposit. As such, it appears that the larger individuals can be accounted for by normal alluvial processes occurring at that locality during deposition of the Brandywine gravel.

It was mentioned that the gravel beds exposed in the Gordon's Corners pit showed no strongly contrasting textures. The larger cobbles thus appear to be distributed throughout the gravel rather than being concentrated in certain beds. This in turn suggests that the larger cobbles were part of the normal stream load, rather than respresenting special deposits laid during occasional floods. Instances are known among gravel deposits in which bed texture varies widely, and it may be that a study of extreme individuals concentrated in particular beds would disclose a history of special events associated with the coarser layers.

If the Brandywine deposits represent accumulation of gravel during an episode of alluvial-plain building, as is believed, it may be possible to relate the cobbles to the competence of the transporting streams. The competent velocity is defined as the slowest mean current velocity capable of initiating movement of particles of given size. As *Menard* [1950] points out, the mean velocity appears to be most appropriate for the interpretation of ancient deposits owing to limitations on determination of critical tractive force or critical frictional velocities from the size data of ancient deposits.

Although data on stream competence for large particles are not abundant, Menard assembled the test data of the *U.S. Waterways Experiment Station* [1935] on pebbles and cobbles, and supplemented them with his own observations in a tidal sluiceway. His graphs show that particles of diameter of the order of three cm require competent velocities of about 150 cm/sec, and that motion of these particles ceases when the velocity drops below about 60 cm/sec. If it is valid to extrapolate

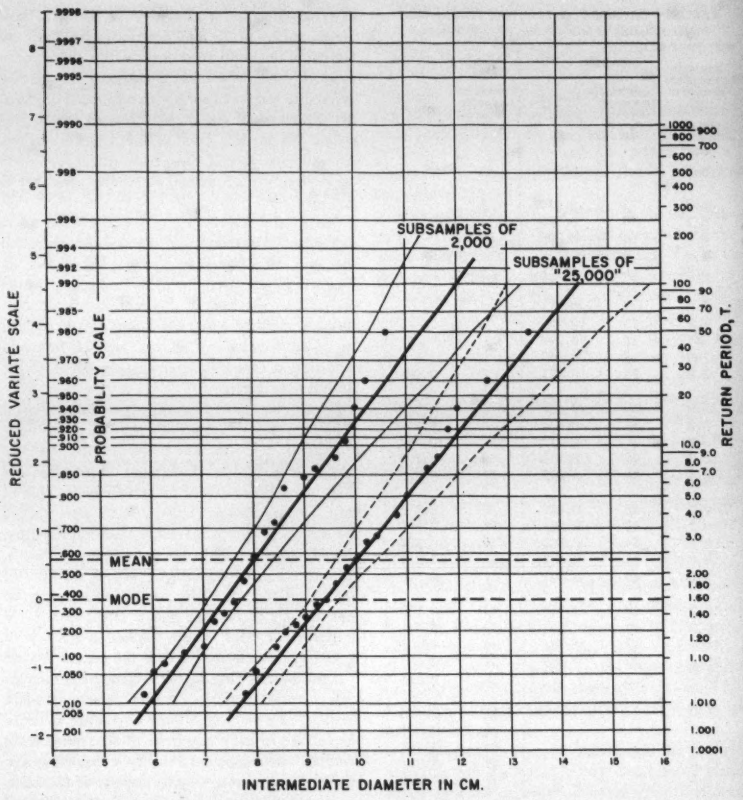

FIG. 2 – Extreme-value distributions fitted to the data of Table 1, showing 95 pct confidence limits

the data to diameters of the order found in the present study, it would appear that deposition of cobbles with diameter of the order of 10 cm would occur in currents of speed slower than about 150 cm/sec. This is equivalent to velocities of about 5 ft/sec.

Establishment of the exact relation between cobble diameter and stream competence is not a purpose of this paper; assuming that such relations could be established, it would become possible to study the occurrence of extreme individuals at various points over a gravel sheet, and to prepare a map of the inferred stream velocities associated with the larger particles. Such a map, used in conjunction with other regional maps, may be helpful in evaluating the changing conditions as mean particle size diminishes in the direction of transport. The Gordon's Corners pit represents a coarse phase of the Brandywine deposits, and within a relatively few miles to the southeast the coarsest particles decrease to intermediate diameters of about 5 cm. According to Menard's graphs, these particles would come to rest at velocities of about 2 to 3 ft/sec.

In addition to its possible use for mapping inferred competence, and in helping decide whether extremely large cobbles or boulders may belong to the local deposit, there may be some advantages

to expressing the particle size characteristics of stream deposits in terms of extreme-value parameters. Many stream deposits have a wide range of particle sizes, and the average diameter (median, geometric mean, etc.) of a single sample may shed little light on the size of the largest particles in the deposit. If an extreme-value distribution for the stream deposits were prepared by measuring the largest pebble in subsamples of fixed size, the mode, median, or mean of such a distribution, which can be read graphically, would give a good idea of the coarser parts of the deposit. This value, used with the corresponding average particle size of the deposit as a whole, would contribute useful information for comparison of stream deposits.

In developing the extreme-value distribution for this purpose it is advantageous to use subsamples of fixed size. The subsample size may depend in part on local sampling problems, but by means of the relationship for different subsample sizes, discussed in the Appendix below, the data may be expressed in some common subsample size for comparative purposes.

An alternative to the use of the extreme-value distribution as a measure of the extremes in the sample might be thought to be the 95 or 99 percentile of the original particle size distribution. These extreme percentiles from a single distribution do not, however, furnish as much information as an average of a set of extremes from a series of size distributions.

Concluding remarks—The present study was based on a 'trial run' of pebble measurements to see whether the data lend themselves to study by extreme-value theory. Despite the approximate nature of the field measurements and the relatively crude estimates of subsample size, the data agreed well with theoretical requirements. This favorable result suggests that other sedimentary deposits may be investigated by these methods.

The writers are indebted to F. J. Pettijohn and John Schlee of John Hopkins University, and R. M. Garrels of Harvard University for field assistance and helpful suggestions in this preliminary study.

Appendix

This Appendix on some extreme-value theory is included mainly as an introduction for geological readers who may wish to apply similar methods to other problems. The theoretical distribution of extremes (largest values) of very large subsamples is in many cases given by the cumulative frequency curve

$$\text{Prob}\{\text{extreme value} < x\} = F(x;u,\beta) = e^{-e^{-y}} \quad (1)$$

where

$$y = (x - u)/\beta \quad (2)$$

Here u is the mode (location of the highest point) of the frequency curve. It defines the position of the curve on the x-axis. The parameter β is a measure of spread related to the standard deviation, σ. It is actually $\sigma\sqrt{6}/\pi = 0.7797\sigma$ for the distribution (1). The frequency (density) function may be obtained in the usual way by differentiating (1) with respect to x, but it is not needed for present purposes.

The distribution (1) is fitted to a set of extremes by determining the parameters u, β in some manner. The following values, as well as the confidence limits in Figure 2, were computed by a method described by Lieblein [1954]:

Samples of 2000	*Samples of 25,000*
$u_I = 7.43$ cm	$u_{II} = 9.38$ cm
$\beta_I = 0.99$ cm	$\beta_{II} = 1.09$ cm

For data that fit as well as the present examples, it is usually sufficient to plot the values $[x_i, i/(n + 1)]$ from Table 1, draw the best straight line by eye, and read the parameter values graphically. The confidence band may also be omitted in such instances.

Graphical determination of u, β depends on the fact that the quantity y in (1), the reduced variate, is uniformly spaced, as in the vertical scale of Figure 2. This double scale shows the correspondence between y and the cumulative probability. Greater precision for converting one of these quantities into the other may be obtained from recent tables [*U. S. National Bureau of Standards*, 1953]. The relationship between the reduced variate y and the observed variate x (horizontal scale in Figure 2) is the straight line (2) with slope $1/\beta$, and this is also the equation of the fitted line in the figure. Thus the two fitted distributions may be represented as

$$\left.\begin{aligned} \text{(I)}\ y &= (x - u_I)/\beta_I = (x - 7.43)/0.99 \\ \text{(II)}\ y &= (x - u_{II})/\beta_{II} = (x - 9.38)/1.09 \end{aligned}\right\} \quad (3)$$

Equations (3) indicate that $u = x$ when $y = 0$. Hence, the mode is read graphically as the x-value associated with $y = 0$ on the reduced variate scale. From Figure 2 the modes are 7.4 and 9.4. The value β is found by taking another pair of values (x,y) and substituting in the relation $\beta = (x - u)/y$. Thus, taking the value $y = 2$ on the reduced variate scale for the 2000 line in Figure 2

yields the x-value 9.4. From this, $\beta_I = 1.0$. For the 25,000 line, $\beta_{II} = 1.1$. These values are also in good agreement with the computed values.

The relation between subsample sizes depends on the fact that when one takes the largest values from each of several groups and then takes the largest one from among these selected values, the result is the same as though the single largest value from among all the items in all the groups had been taken. That is, *the largest among largest values is the largest among all the original values*. This fundamental postulate is the cornerstone of extreme-value theory. It leads directly to (1) by theoretical reasoning [Fisher and Tippett, 1928].

The transition from subsamples of 2000 to those about 12 times as large is obtained by considering the larger subsample, of size 25,000, to consist of 12 random samples each of size 2000. The extreme in the smaller subsample is a variable having the distribution of the general form $F(x;u,\beta)$ in (1). According to the fundamental postulate the extreme from the larger subsample may be thought of as the extreme of 12 or, in general, of n independent extremes each represented by (1). Accordingly, the new distribution is

$$F_n(x) = F^n(x;u,\beta) = \exp[-ne^{-(x-u)/\beta}] = \exp[-e^{-[x-(u+\beta\ln n)]/\beta}] \quad (4)$$

where ln is the natural logarithm. Expression (4) is the same as (1) except that the parameter u is replaced by the new parameter $u' = u + \beta \ln n$. The parameter β remains unchanged. The distribution thus retains its shape and the only change in the fitted straight line is to shift it along the x-axis, without change of slope, a distance $u' - u = \beta \ln n$, where n is the factor by which subsample size increases. This relationship may be used to convert data for one subsample size to another subsample size n times as large.

If in (1) and (4) the value of x is taken sufficiently large to make the probabilities $F(x)$, $F_n(x)$ close to unity, an expression for n may be derived that may be used in checking the field estimates of relative subsample size. By means of the relation $1 - \exp(-z) \doteq z$, which holds approximately for small z, it may be shown that

$$\frac{1 - F_n(x)}{1 - F(x)} \doteq \exp[(x - u)/\beta - (x - u - \beta \ln n)/\beta] = n \quad (5)$$

The two estimates $\beta_I = 0.99$ and $\beta_{II} = 1.09$ for the same parameter β are felt to be in reasonable agreement under the circumstances. The difference of about ten per cent is probably accounted for by sampling variability and by the relatively coarse method of field measurement. As mentioned above, the field estimates of relative subsample size can be checked by relation (5) to see how good these judgments were. The numerator and denominator in the first member of this relation are the complements of the probability values on the vertical scale in Figure 2. The numerator, $1 - F_n(x)$, is read from the right-hand line (subsamples of 25,000) for, say, $x = 14$ cm. The resulting value is $P_2 = 1 - 0.985 = 0.015$. Similarly, the denominator, $1 - F(x)$, is read for the left-hand line in the figure for the same value of x, giving $P_1 = 1 - 0.9985 = 0.0015$. The ratio $P_2/P_1 = 10$ then gives the computed value of n according to (5). This suggests that the subsample sizes were in the relation of 1:10 instead of 1:12.

In the present case the smaller subsample size of 2000 pebbles is believed to be reasonably accurate, so that the larger subsample size, estimated in the field as 25,000, should have been closer to 20,000. The field estimates of subsample size have been retained in the text because they represent judgments made at the time, but the present development suggests that if some care is used to estimate one subsample size, relation (5) may be used to estimate the order of magnitude of the size of larger subsamples.

The lack of exact agreement between field estimates and calculated subsample size does not imply that the data do not follow the extreme value law. If anything, it indicates that field measurements and estimates of subsample size should be made with care.

From a practical point of view extrapolation of subsample size is satisfactory only when the subsample size is very large, preferably in the thousands, but perhaps in certain cases (for example, floods) also in the hundreds and possibly less. This follows because extreme-value theory is an *asymptotic* theory, becoming more exact only as subsample size increases without limit. It is to be noted that this statement applies to the number of individuals in each subsample, and not to the size of the sample (that is, the number of sets from each of which one extreme was taken). In the present case the number of subsamples was 50, but smaller sets of 20 or 30 (and even 6 or less [Lieblein, 1954]) can be treated by extreme-value analysis.

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Discordant Uranium-Lead Ages, I

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Abstract—A graphical procedure is described for rapid calculation of discordant uranium-lead ages resulting from multiple episodes of uranium-lead fractionation. A proof of the validity of this graphical procedure is given. The graphical procedure is extended to permit the calculation of the effect of the presence of primary radiogenic lead and of constant loss of intermediate daughter products.

Introduction—The element uranium has two long-lived isotopes, U^{238} and U^{235}, the final decay products of which are Pb^{206} and Pb^{207}, respectively. Measurement of the uranium concentration and the concentration of radiogenic Pb^{206} and Pb^{207} in a chemical system (such as a mineral) containing uranium permits the calculation of two uranium-lead ages, the U^{238}-Pb^{206} age, T_1 and the U^{235}-Pb^{207} age, T_2 calculated from the equations of radioactive decay

$$\left.\begin{aligned} T_1 &= \frac{1}{\lambda_{U^{238}}} \ln\left(\frac{Pb^{206}}{U^{238}} + 1\right) \\ T_2 &= \frac{1}{\lambda_{U^{235}}} \ln\left(\frac{Pb^{207}}{U^{235}} + 1\right) \end{aligned}\right\} \quad (1)$$

In this discussion it will be convenient to designate the U^{238}-Pb^{206} decay by superscript or subscript 1, and the U^{235}-Pb^{207} decay by the subscript 2. Thus, equations (1) become

$$\left.\begin{aligned} T_1 &= \frac{1}{\lambda_1} \ln\left(\frac{D_1}{P_1} + 1\right) \\ T_2 &= \frac{1}{\lambda_2} \ln\left(\frac{D_2}{P_2} + 1\right) \end{aligned}\right\} \quad (1a)$$

where the λ's are the decay constants, and D and P refer to the daughter and parent concentrations, respectively.

Where these two ages are found to be equal to one another, the ages are said to be 'concordant.' When they are unequal, they are said to be 'discordant.'

These two calculated ages will be equal to one another and to the true age of the mineral if the following assumptions are fulfilled: (a) There have been no gains or losses of uranium or lead during the time since the formation of the system. (b) There have been no gains or losses of intermediate members of the radioactive decay scheme, for example, radon, or ionium. (c) Proper corrections have been made for the initial concentration of Pb^{206} and Pb^{207}. (d) The chemical analyses have been properly performed and the correct decay constants λ_1 and λ_2 have been used. When these assumptions have been fulfilled, the ages will be concordant; when they are not fulfilled, the ages will be either discordant or 'accidentally' concordant.

These papers will discuss discordance and accidental concordance arising from failure of assumptions (a), (b), and (c), which may be considered 'intrinsic discordance' as opposed to 'technical' discordance resulting from failure of assumption (d).

In this first paper a graphical scheme will be presented for the calculation of the effects of failure of assumption (a) at discreet episodes in the history of the mineral, and a discussion will be given of the effects of failure of assumptions (b) and (c), within the framework of this graphical method. In a subsequent publication this graphical procedure will be applied to problems of geochronology, namely, the interpretation of regularities in a group of discordant ages such as those by *Ahrens* [1955] as well as the inference of the true age of a group of cogenetic minerals giving discordant ages, even when no regularities are present. This graphical scheme will make use of a diagram (Fig. 1) in which the mole ratio Pb^{206}/U^{238} (D_1/P_1) is plotted as the ordinate and the mole ratio Pb^{207}/U^{235} (D_2/P_2) as the abscissa. In the case of concordant ages, for every age $\tau_0 = T_1 = T_2$ there will correspond unique values of D_1/P_1 and D_2/P_2 defined by the equations

$$\left.\begin{aligned} \frac{D_1}{P_1} &= e^{\lambda_1 \tau_0} - 1 \\ \frac{D_2}{P_2} &= e^{\lambda_2 \tau_0} - 1 \end{aligned}\right\} \quad (2)$$

The locus of these values for $0 < \tau_0 < \infty$ is the curve marked 'concordia' on Figure 1.

Description of the graphical procedure—The procedure will be described without proof. The proof of its validity is found in the following section. Consider a sample of uranium mineral (or more generally a chemical system containing uranium) having a true age τ_0. If the assumptions

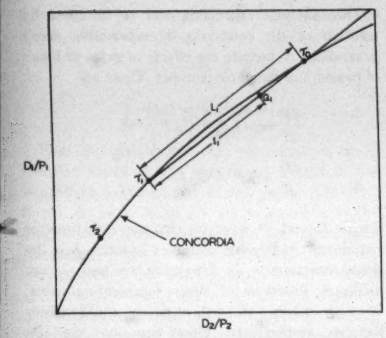

FIG. 1 – D/P diagram illustrating the graphical procedure for calculating the uranium-lead ages resulting from a given history of uranium-lead fractionation.

(a), (b), (c), and (d) are valid, the point characteristic of this mineral sample will lie on concordia at τ_0. If the mineral has lost lead or uranium or gained uranium during a geologically brief episode at a time τ_1 years ago, the position of the point (Q_1) characteristic of this mineral may be found by the following procedure: (1) Draw a straight line passing through the point on the curve 'concordia' corresponding to a true age τ_0 and that corresponding to a true age τ_1. (2) Defining the length of the straight segment $\overline{\tau_0\tau_1} = L_1$, measure off a distance along this segment of length $l_1 = R_1L_1$ from τ_1. R_1 is the ratio by which D_1/P_1 and D_2/P_2 changed at time τ_1. That is,

$$R_1 = \frac{(D/P)_{\text{immediately after loss}}}{(D/P)_{\text{immediately before loss}}}$$

The end of this segment is the desired point Q_1. In the case of lead loss, it is assumed that R is the same for both the lead isotopes, that is, that the lead which is lost has the same isotopic composition as the total lead which was present in the total lead which was present in the mineral. This is not a very severe restriction for lead loss, but it must be noted that lead addition will not in general fulfill this condition, and therefore the graphical procedure has been limited to losses of lead or uranium or additions of uranium. This case where R is unequal for D_1/P_1 and D_2/P_2 is discussed in the section on *Extensions of the graphical procedure*. For example, if half the lead were lost with no loss of uranium, the $R_1 = \frac{1}{2}$. If, on the other hand, $\frac{1}{3}$ of the uranium were lost, $R_1 = \frac{2}{3}$, and $l_1 = \frac{2}{3}L_1$.

From the procedure given above, it is seen that regardless of how much uranium or lead is lost during this episode, the resulting point (Q_1) will lie on this straight line. From the coordinates of the point (D_1/P_1, D_2/P_2) found by this procedure, the discordant uranium-lead ages can be calculated by use of Eq. (2). Thus the effect of a single episode of uranium-lead fractionation has been determined.

For the special case $R_1 = 1$, that is, no fractionation, the result is that the point Q_1 characterizing the mineral remains on the curve 'concordia' at τ_0. If, on the other hand, all the lead were lost at τ_1, perhaps due to a remineralization with exclusion of lead, then $R_1 = 0$ and $l_1 = 0$ and the point characterizing the sample will lie on the curve 'concordia' at τ_1. In this case the age of the sample can be considered more properly to be τ_1.

For the case of multiple episodes of uranium-lead fractionation, the resulting point Q_n can be found by extension of this same procedure. Assume a second fractionation R_2 occurred at a later time τ_2. The effect of this is found by the following procedure: (1) Draw a straight line between the point Q_1 (found by the above procedure for the first fractionation) and the point τ_2 on concordia. (2) Defining the length of the straight segment $\overline{Q_1\tau_2} = L_2$, the desired point Q_2 will lie at a distance $l_2 = R_2L_2$ from τ_2 on concordia. For a third fractionation at τ_3, the procedure is repeated with $\overline{Q_2\tau_3} = L_3$ and $l_3 = R_3L_3$ giving point Q_3. For the case of n fractionations, the procedure is repeated n times, finally resulting in a point Q_n. From the coordinates of this point, the discordant ages T_1 and T_2 can be calculated. These are the ages that would be measured for a mineral with a true age τ_0 that has undergone n fractionations R_i, $(i = 1, 2, \cdots n)$ at times τ_i in the past.

This construction is illustrated by the following example, illustrated by Figure 2. Consider a uranium mineral having a true age of 1350 million years. 900 million years ago the uranium and lead within this mineral were partially separated. At this time 17 pct of the lead within the mineral was lost, while at the same time 50 pct of the uranium was lost. As a consequence of this fractionation, the ratios D_1/P_1 and D_2/P_2 change by a factor 1.65 and $R_1 = 1.65$. In recent times (essentially zero million years ago) a second fractionation occurred, resulting in the loss of 27 pct of the lead present in the mineral, with a loss of

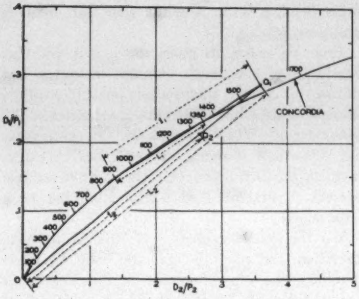

FIG. 2 – D/P diagram illustrating a numerical example of the graphical procedure

only one per cent of the uranium. Hence $R_2 = 0.74$.

Following the graphical procedure described above, a straight line is drawn through the points 900 and 1350 on the curve 'concordia.' The point Q_1 is found by measuring the separation of these two points and measuring off a distance 1.65 times this separation along this line from the point 900. Q_2 is found by drawing a similar line between 0 and Q_1, and measuring off the proper distance from 0. This distance is 0.74 times the distance between 0 and Q_1.

Since this hypothetical mineral underwent two fractionations, it is characterized by the point Q_2. From the coordinates of this point ($D_1/P_1 = 0.214$, and $D_2/P_2 = 2.64$) the ages $T_1 = 1260$ *m y* and $T_2 = 1330$ *m y* are calculated from (1a). An exact analytic calculation of this example gives $T_1 = 1250$ and $T_2 = 1330$ *m y*. The accuracy of this graphical procedure depends only on the care with which the construction is made.

The effect of a continuous process can be approximated by graphically calculating the continuous process as a sum of episodic fractionations with the interval between episodes small.

Proof of the graphical procedure—The graphical procedure outlined above will be proved to be correct by showing that the coordinates of the resulting point Qn corresponds to the coordinates D_1/P_1 and D_2/P_2 which would be found by an analytic calculation of the effect of n fractionations $R_i (i = 1, 2, \cdots n)$ at times τ_1 in the past. In the following discussion the symbol t will be used to indicate time increasing in the usual sense and having the value zero at the time of mineralization. The symbol τ_1 will be used to indicate the time of an event measured back from the present.

This analytic expression will be obtained by solution of the equations of radioactive decay generalized to include the effects of gains or losses of parent and daughter isotopes. These are

$$\left.\begin{aligned} \frac{dP}{dt} &= -\lambda P + G_P P \\ \frac{dD}{dt} &= \lambda P + G_D D \end{aligned}\right\} \quad (3)$$

where P and D refer to the concentrations of parent and radiogenic daughter isotopes, λ is the decay constant $= ln\ 2/\text{half-life}$, G_P and G_D are arbitrary functions of times representing gains, ($G > 0$) or losses ($G < 0$) of parent and daughter isotopes, respectively. These equations may be solved by elementary methods with the result

$$\frac{D}{P} = \lambda e^{F(\tau_0)} \int_0^{\tau_0} e^{-F}\, dt \quad (4)$$

where

$$F = \lambda t + \int (G_D - G_P)\, dt,$$

and τ_0 is the true age of the mineral. (An equation essentially the same as (4) has also been derived by F. Wickman and his discussion of it will be published in the report of the Pennsylvania State University Conference on Nuclear Geophysics, September, 1955).

It may be seen by inspection of the form of F in (4) that a gain of parent represented by a function G_P will have exactly the same effect on the ratio D/P as a loss of daughter with $G_D = -G_P$. It will therefore be impossible to distinguish between loss of parent and gain of daughter or between gain of parent and loss of daughter by the effect on the ratio D/P. Without any loss of generality the expression $(G_D - G_P)$ can be replaced by an arbitrary function of time G, which will represent the net effect of gains or losses of parent and daughter. In this work where 'loss of daughter' is used, it will be understood that the possibility of gain of parent is also implied, and similarly for loss of parent.

By assuming different forms of G, the effects of different kinds of fractionation processes can be calculated. For the case of n episodic fractionations at times τ_i, $i = 1, \cdots n$ the function G will be given by

$$G = \sum_{i=1}^{n} a_i\, \delta[t - (\tau_0 - \tau_i)] \quad (5)$$

where $\delta[t - (\tau_0 - \tau_i)]$ is the Dirac δ-function [*Dirac*, 1949] defined by

$$\left.\begin{aligned} \delta(x) &= 0 \quad x \neq 0 \\ \int_a^a \delta(x) &= 1 \quad a > 0 \end{aligned}\right\} \tag{6}$$

Thus the δ-function can be visualized as a function which is zero everywhere except in the immediate neighborhood of one point. Similarly, G will be zero except at the moments τ_i. The difficulties of mathematical rigor associated with the use of (6) can be resolved in the usual way by replacing the δ-function by a gaussian and taking the standard deviation to be arbitrarily small. Thus the fractionation can be thought of as taking place over a period of time which is geologically short, for example, a million years.

By substitution of G (5) into (4) and integration, one obtains

$$\frac{D}{P} = \sum_{j=1}^{n} e^{\sum_{i=j}^{n} a_i} [e^{\lambda\tau_{j-1}} - e^{\lambda\tau_j}] + e^{\lambda\tau_n} - 1 \tag{7}$$

The differential equations (3) can be combined in the form

$$\frac{d}{dt}\left(\frac{D}{P}\right) = \lambda + \left(\frac{D}{P}\right)(G + \lambda) \tag{8}$$

or

$$\frac{d}{dt} \ln\left(\frac{D}{P}\right) = \lambda \frac{P}{D} + G + \lambda \tag{9}$$

This equation will be integrated over a short period of time (2ϵ) including one of the episodes τ_i.

$$\int_{\tau_0-(\tau_i-\epsilon)}^{\tau_0-(\tau_i-\epsilon)} \frac{d}{dt} \ln\left(\frac{D}{P}\right) dt = \lambda \int_{\tau_0-(\tau_i+\epsilon)}^{\tau_0-(\tau_i-\epsilon)} \frac{P}{D}\, dt + \int_{\tau_0-(\tau_i+\epsilon)}^{\tau_0-(\tau_i-\epsilon)} \Sigma a_i \delta(t - (\tau_0 - \tau_i))\, dt + \lambda t \Big|_{\tau_0-(\tau_i+\epsilon)}^{\tau_0-(\tau_i-\epsilon)} \tag{10}$$

or

$$\ln \frac{\left(\frac{D}{P}\right)_{\tau_i-\epsilon}}{\left(\frac{D}{P}\right)_{\tau_i+\epsilon}} = \lambda \int_{\tau_0-(\tau_i+\epsilon)}^{\tau_0-(\tau_i-\epsilon)} \frac{P}{D}\, dt + a_i + 2\epsilon\lambda \tag{11}$$

as $\epsilon \to 0$

$$\ln \frac{\left(\frac{D}{P}\right)_{\text{after loss}}}{\left(\frac{D}{P}\right)_{\text{before loss}}} \to a_i \tag{12}$$

then

$$\frac{\left(\frac{D}{P}\right)_{\text{immediately after loss}}}{\left(\frac{D}{P}\right)_{\text{immediately before loss}}} = e^{a_i} \tag{13}$$

or in accordance with the definition of R_i

$$R_i = e^{a_i} \tag{14}$$

(The proof of (14) has been materially simplified as a result of a suggestion by G. Wasserburg.)

Eq. (7) can now be rewritten as

$$\frac{D}{P} = \sum_{j=1}^{n} [e^{\lambda\tau_{j-1}} - e^{\lambda\tau_j}] \prod_{i=j}^{n} R_i + (e^{\lambda\tau_n} - 1) \tag{15}$$

This is the general expression for the ratio D/P resulting from the decay of parent in a mineral of true age τ_0 which has undergone n fractionations, R_i at times τ_i. For a uranium mineral there will be two such expressions, one giving D_1/P_1 and the other D_2/P_2.

Using this general expression, the graphical procedure will be proved by induction. (a) It will first be shown that the point $(D_1/P_1, D_2/P_2)$ found by the graphical procedure agrees with the result of the analytic calculation for the case $n = 1$. (b) It then will be shown that if the construction is valid for $n = m$, it will also be valid for $n = m + 1$.

Demonstration of (a) and (b) above will prove the construction valid for any number of fractionations.

Regarding (a), by substituting $n = 1$ into (15) we obtain

$$\left.\begin{aligned} \frac{D_1}{P_1} &= R_1[e^{\lambda_1\tau_0} - e^{\lambda_1\tau_1}] + e^{\lambda_1\tau_1} - 1 \\ \frac{D_2}{P_2} &= R_1[e^{\lambda_2\tau_0} - e^{\lambda_2\tau_1}] + e^{\lambda_2\tau_1} - 1 \end{aligned}\right\} \tag{16}$$

These are the parametric equations for the locus of points representing minerals having a true age τ_0 and which underwent a fractionation R_1 at a time τ_1 in the past. According to the graphical construction, this locus should be a straight line passing through τ_0 and τ_1 on the curve 'concordia.'

That it passes through τ_0 can be seen by letting the parameter $R_1 = 1$, then

$$\left.\begin{aligned} \frac{D_1}{P_1} &= e^{\lambda_1\tau_0} - 1 \\ \frac{D_2}{P_2} &= e^{\lambda_2\tau_0} - 1 \end{aligned}\right\} \tag{17}$$

which are the coordinates of τ_0 on the curve 'concordia' as given by (2).

Similarly when the parameter $R_1 = 0$

$$\left.\begin{aligned}\frac{D_1}{P_1} &= e^{\lambda_1\tau_1} - 1\\ \frac{D_2}{P_2} &= e^{\lambda_2\tau_1} - 1\end{aligned}\right\} \tag{18}$$

which are the coordinates of τ_1 on concordia. By differentiating each of (16) with respect to the parameter R_1 and dividing, we obtain the slope of the locus

$$\frac{d\left(\frac{D_1}{P_1}\right)}{d\left(\frac{D_2}{P_2}\right)} = \frac{e^{\lambda_1\tau_0} - e^{\lambda_1\tau_1}}{e^{\lambda_2\tau_0} - e^{\lambda_2\tau_1}} \tag{19}$$

which is independent of R_1, that is of the position of the point on the locus. The slope is therefore the same at all points on the locus, that is the line is straight.

According to the graphical construction, the distance along this line (l) between τ_1 on concordia and the point characterizing a mineral which underwent a fractionation R_1 at τ_1 is given by $l_1 = R_1L_1$ where L_1 is the length of the segment $\tau_0\tau_1$. The length can be found by use of the coordinates of τ_0 and τ_1 on concordia from equations (17) and (18) and the Pythogorean theorem to be

$$L_1^2 = [e^{\lambda_1\tau_0} - e^{\lambda_1\tau_1}]^2 + [e^{\lambda_2\tau_0} - e^{\lambda_2\tau_1}]^2 \tag{20}$$

By using (16) and (18) and the Pythogorean theorem we obtain similarly

$$l_1^2 = R_1^2[e^{\lambda_1\tau_0} - e^{\lambda_1\tau_1}]^2 + R_1^2[e^{\lambda_2\tau_0} - e^{\lambda_2\tau_1}]^2 \tag{21}$$

and by comparing (20) and (21) we obtain

$$l_1 = R_1L_1 \text{ thus completing the proof for } n = 1. \tag{22}$$

Regarding (b) if it is assumed that the graphical construction is valid for $n = m$, it will now be shown that it is valid for $n = m + 1$.

The coordinates of a point which has undergone $n = m + 1$ fractionations will be

$$\left.\begin{aligned}\frac{D_1}{P_1} &= \sum_{j=1}^{m+1}[e^{\lambda_1\tau_{j-1}} - e^{\lambda_1\tau_j}]\prod_{i=j}^{m+1}R_i + (e^{\lambda_1\tau_{m+1}} - 1)\\ \frac{D_2}{P_2} &= \sum_{j=1}^{m+1}[e^{\lambda_2\tau_{j-1}} - e^{\lambda_2\tau_j}]\prod_{i=j}^{m+1}R_i + (e^{\lambda_2\tau_{m+1}} - 1)\end{aligned}\right\} \tag{23}$$

For the case $R_{m+1} = 1$, that is, no fractionation at stage $(m + 1)$ the point will have the coordinates

$$\begin{aligned}\frac{D_1}{P_1} &= \sum_{j=1}^{m}[e^{\lambda_1\tau_{j-1}} - e^{\lambda_1\tau_j}]\prod_{i=1}^{m}R_i + (e^{\lambda_1\tau_m} - e^{\lambda_1\tau_{m+1}}) + (e^{\lambda_1\tau_{m+1}} - 1) \qquad (24)\\ &= \sum_{j=1}^{m}[e^{\lambda_1\tau_{j-1}} - e^{\lambda_1\tau_j}]\prod_{i=j}^{m}R_i + (e^{\lambda_1\tau_m} - 1)\end{aligned}$$

and similarly

$$\frac{D_2}{P_2} = \sum_{j=1}^{m}[e^{\lambda_2\tau_{j-1}} - e^{\lambda_2\tau_j}]\prod_{i=j}^{m}R_i + (e^{\lambda_2\tau_m} - 1)$$

which according to (15) are the coordinates of a point Q_m which has undergone m fractionations R_i at times τ_i. Thus the locus of a point which has undergone $m + 1$ fractions R_i at times τ_i passes through this point. For the case $R_{m+1} = 0$, we get the point

$$\frac{D_1}{P_1} = e^{\lambda_1\tau_{m+1}} - 1 \tag{25}$$

and

$$\frac{D_2}{P_2} = e^{\lambda_2\tau_{m+1}} - 1, \quad \text{that is, the point } \tau_{m+1} \text{ on concordia}$$

By differentiating (23) with respect to R_{m+1} and taking their ratio we obtain

$$\frac{d\left(\frac{D_1}{P_1}\right)}{d\left(\frac{D_2}{P_2}\right)} = \frac{\sum_{j=1}^{m}[e^{\lambda_1\tau_{j-1}} - e^{\lambda_1\tau_j}]\prod_{i=j}^{m}R_i + (e^{\lambda_1\tau_m} - e^{\lambda_1\tau_{m+1}})}{\sum_{j=1}^{m}[e^{\lambda_2\tau_{j-1}} - e^{\lambda_2\tau_j}]\prod_{i=j}^{m}R_i + (e^{\lambda_2\tau_m} - e^{\lambda_2\tau_{m+1}})} \tag{26}$$

which is independent of R_{m+1}. Thus the locus of points corresponding to minerals which have undergone varying fractionations R_{m+1} at time τ_{m+1} is a straight line passing through Q_m and τ_{m+1} on concordia, as given by the graphical procedure.

The distance L_{m+1} between Q_m and τ_{m+1} on concordia will be (by use of the Pythogorean theorem)

$$\begin{aligned}L_{m+1}^2 = &\left\{\sum_{j=1}^{m}[e^{\lambda_1\tau_{j-1}} - e^{\lambda_1\tau_j}]\prod_{i=j}^{m}R_i + (e^{\lambda_1\tau_m} - 1) - (e^{\lambda_1\tau_{m+1}} - 1)\right\}^2\\ &+ \left\{\sum_{j=1}^{m}[e^{\lambda_2\tau_{j-1}} - e^{\lambda_2\tau_j}]\prod_{i=j}^{m}R_i + (e^{\lambda_2\tau_m} - 1) - (e^{\lambda_2\tau_{m+1}} - 1)\right\}^2 \qquad (27)\end{aligned}$$

collecting terms

$$L^2_{m+1} = \left\{ \sum_{j=1}^{m+1} [e^{\lambda_1 \tau_{j-1}} - e^{\lambda_1 \tau_j}] \frac{\prod_{i=j}^{m+1} R_i}{R_{m+1}} \right\}^2 + \left\{ \sum_{j=1}^{m+1} [e^{\lambda_2 \tau_{j-1}} - e^{\lambda_2 \tau_j}] \frac{\prod_{i=j}^{m+1} R_i}{R_{m+1}} \right\}^2 \quad (28)$$

The distance l_{m+1} between τ_{m+1} on the curve 'concordia' and the point characteristic of a mineral which has undergone $m+1$ fractionations R_i at times τ_i will be

$$l^2_{m+1} = \left\{ \sum_{j=1}^{m+1} [e^{\lambda_1 \tau_{j-1}} - e^{\lambda_1 \tau_j}] \prod_{i=j}^{m+1} R_i \right\}^2 + \left\{ \sum_{j=1}^{m+1} [e^{\lambda_2 \tau_{j-1}} - e^{\lambda_2 \tau_j}] \prod_{i=j}^{m+1} R_i \right\}^2 \quad (29)$$

By comparison of (28) and (29)

$$l^2_{m+1} = R^2_{m+1} L^2_{m+1}$$

Thus the locus of points characteristic of minerals which have undergone m fractionations R_i at times τ_i and an additional fractionation R_{m+1} at time τ_{m+1} will be a straight line passing through the point Q_m and the point τ_{m+1} on concordia. For a given fractionation R_{m+1}, the distance of the point from τ_{m+1} on concordia will be equal to $R_{m+1}L_{m+1}$ where L_{m+1} is the distance from Q_m to τ_{m+1} on concordia. By hypothesis the point Q_m (which represents the point characteristic of minerals which have undergone m fractionations R_i, $i = 1, 2, \cdots m$ at times τ_i) is given correctly by the graphical procedure. It has been shown above that the analytical calculation is in agreement with the graphical procedure for finding Q_{m+1} from Q_m. Therefore, the point Q_{m+1} found by the analytical calculation will be the same point found by the graphical procedure, thus completing the proof.

Extensions of the graphical procedure—In the foregoing discussion a procedure has been demonstrated for graphically calculating the discordant uranium-lead ages which will result when a mineral undergoes a series of episodes of uranium-lead fractionation (failure of assumption a). A brief discussion will now be given of the calculation of the effects of failure of assumptions (b), and (c) as well as the effect of unequal fractionation of Pb^{206} and Pb^{207}.

Loss of intermediate decay products—For the equilibrium case (implicit in (1)) the loss of an intermediate decay product is equivalent to the decay constant λ for the growth of daughter being less than the decay constant λ for the decay of parent (3).

Therefore, (3) can be replaced by

$$\left.\begin{aligned} \frac{dP}{dt} &= -\lambda P + G_P P \\ \frac{dD}{dt} &= \lambda \Lambda(t) P + G_D D \end{aligned}\right\} \quad (30)$$

where $\Lambda(t)$ represents the fraction of intermediate decay product which is retained.

These equations can be integrated to give

$$\frac{D}{P} = \lambda e^{F(\tau_0)} \int_0^{\tau_0} \Lambda(t) e^{-F}\, dt \quad (31)$$

It may be expected that Λ will be different for the two decay systems, U^{238} and U^{235}.

For the case of constant loss of intermediate decay product the function Λ can be taken outside the integral. In this case the value of D/P will be decreased by a factor Λ. For combined multiple fractionation and constant intermediate product loss, the resulting values of D_1/P_1 and D_2/P_2 can be found by first applying the graphical procedure and finally multiplying D_1/P_1 by Λ_1, and D_2/P_2 by Λ_2.

Presence of primary radiogenic lead—Eq. (3) can be generalized to include the effects of primary radiogenic lead with the result

$$\frac{D}{P} = e^{F(\tau_0)} \left[\left(\frac{D}{P}\right)_0 e^{-F(0)} + \int_0^{\tau_0} \lambda e^{-F}\, dt \right] \quad (32)$$

where $(D/P)_0$ is the initial radiogenic daughter to parent ratio.

For the case of multiple episodic fractionations

$$\left(\frac{D}{P}\right) \sum_{j=1}^{n} [e^{\lambda \tau_{j-1}} - e^{\lambda \tau_j}] \prod_{i=j}^{n} R_i + (e^{\lambda \tau_n} - 1) + \left(\frac{D}{P}\right)_0 e^{\lambda \tau_0} \prod_{i=1}^{n} R_i \quad (33)$$

which differs from (15) only in the last term. Therefore, the effect of primary radiogenic daughter can be found by applying the graphical procedure and finally adding the term

$$\left(\frac{D}{P}\right)_0 e^{\lambda \tau_0} \prod_{i=1}^{n} R_i \quad \text{to} \quad \frac{D_1}{P_1} \quad \text{and} \quad \frac{D_2}{P_2} \quad (34)$$

By a proof along the lines of that in *Proof of the graphical procedure*, it can also be shown that the graphical calculation is valid for the case of primary radiogenic daughter if the starting point

for the graphical procedure is taken to the coordinates of τ_0 on concordia augmented by

$$\left(\frac{D}{P}\right)_0 e^{\lambda\tau_0}$$

The effect of unequal fractionation of Pb^{206} and Pb^{207}—As a consequence of an earlier process of uranium-lead fractionation, the uranium in a mineral may be displaced from the lead. The radiogenic lead resulting from the decay of this uranium will then be in the vicinity of the uranium and the two lead isotopes will not be homogeneously distributed within the mineral. Any subsequent fractionation might then cause D_1/P_1 and D_2/P_2 to change by different factors.

In this case it can be shown that the points Q_{m+1} resulting from varying amounts of fractionation of this type will not lie on a straight line between Q_m and τ_{m+1} on concordia but will lie on a curved line between these two points. The coordinate D_1/P_1 for Q_{m+1} will be

$$(e^{\lambda_1\tau_{m+1}} - 1) + R'_{m+1}\left[\left(\frac{D_1}{P_1}\right)_{Q_m} - (e^{\lambda_1\tau_{m+1}} - 1)\right] \quad (35)$$

where R'_{m+1} is the factor by which D_1/P_1 is changed. A similar expression will give (D_2/P_2) for Q_{m+1}.

Concluding remarks—A graphical procedure has been demonstrated for calculating the effects of failure of assumptions (a), (b), and (c). By use of this procedure the discordant ages resulting from a given history can be calculated uniquely. However, if the discordant ages are given, it is not possible to infer the history uniquely. This graphical procedure will be found useful, however, in inferring the possible histories of a given geological unit and in some cases the probable history. These applications and their limitations will be discussed in a subsequent publication.

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Discussion of "A Note on the Manning Formula"

VEN TE CHOW

[*Trans.*, **36**, 688, 1955]

Hunter Rouse (Iowa Institute of Hydraulic Research, State University of Iowa, Iowa City, Iowa, received Nov. 28, 1955)—Several statements with regard to the Manning formula that have appeared in this journal in recent months warrant further comment in order that the record may not be misunderstood.

To amplify Chow's admittedly second-hand account of the origin of the formula, the writer submits the following quotation [*Rouse* and *Ince*, 1954–5] based upon the paper itself and upon biographical information supplied by the Institution of Civil Engineers of Ireland:

"Quite a different tack [from those of Kutter and Bazin] had been followed in 1868 by Philippe-Gaspard Gauckler (1826–1905), Inspector General of the Ponts et Chaussées, who—in despair of finding a single formula which would describe the flow in all types of channels—proposed two for use in different slope ranges

$$V = \lambda_1 R^{1/3} S \quad \text{for} \quad S > 0.0007$$

$$V = \lambda_2 R^{2/3} S^{1/2} \quad \text{for} \quad S < 0.0007$$

An expression identical to the second of these was devised and investigated by the Irish engineer, Robert Manning (1816–1897), two decades later. Manning had been born in Normandy the year following the battle of Waterloo, in which his father had taken part. As chief engineer of the Office of Public Works, he was responsible for various drainage, inland-navigation, and harbor projects, and he also served a term as President of the Institution of Civil Engineers of Ireland. Although, judging from his writings, his primary interest was hydrology, in 1889 he presented to the Institution a paper 'On the Flow of Water in Open Channels and Pipes' in which he sought to remedy the various defects he believed to exist in previous resistance formulations. Apparently without knowledge of the Gauckler proposal, he showed that a relationship of the form

$$V = K R^{2/3} S^{1/2}$$

was in better agreement with available data than any in general use. However, not only did he consider the first fractional power inconvenient to use, but he clearly recognized the fact that '. . . if modern formulae are empirical with scarcely an exception, and are not homogeneous, or even dimensional, then it is obvious that the truth of any such equation must altogether depend on that of the observations themselves, and it cannot in strictness be applied to a single case outside them.'

"Manning therefore discarded formulas of the type now associated with his name, proposing instead the dimensionally homogeneous relationship

$$V = C\sqrt{gS}\left[R^{1/2} + \frac{0.22}{m^{1/2}}(R - 0.15m)\right]$$

Herein the factor C is not the Chezy coefficient but a pure number 'which varies with the nature of the surface,' and m (which he introduced for dimensional as well as physical reasons) 'the height of a column of mercury which balances the atmospheric pressure.' At no point did Manning suggest use of the Kutter n in either formula, the coefficient in question being obtained—much as Chezy had originally proposed—from known data for a channel of the type under consideration. What we now call the Manning formula was thus neither recommended nor even devised in full by Manning himself, whereas his actual recommendation received little further attention."

Although Manning did note that "the value of the reciprocal of $[K]$ . . . corresponds closely with that of n," who it was that first began to use the Kutter n in the Gauckler-Manning type of equation is not yet clear, nor are the circumstances known which led to the adoption of the same numerical values of this factor in both the metric and the English system. In any event, the Chezy C thereby became expressible in terms of what were apparently a constant number K, a variable number n, and the $\frac{1}{6}$ power of a length R

$$C = K\frac{R^{1/6}}{n}$$

When it eventually became understood that the Chezy and the Manning relationships could be dimensionally homogeneous only if each side of this equation had the dimension $L^{1/2}/T$, an argument began as to how this dimension should be distributed among the quantities at the right, opinions ranging all the way from entire absorption by K to entire absorption by n.

That the argument still continues is evident from *Kolupaila's* [1955] recent discussion of a paper on the Manning coefficient by *Boyer* [1954], in which he states that ". . . opposite to the widespread fallacious judgment, the Manning coefficient n has no dimension: the same values are used in both metric and English system and that can be easily checked by conversion factors." Now Boyer had originally followed the teaching of the writer

[*Rouse*, 1946, p. 218] that the Manning roughness factor must have the dimension $L^{1/6}$ in order that the ratio $n/R^{1/6}$ assume its proper role as relative-roughness parameter. In his closing discussion, however, *Boyer* [1955] seemed almost to welcome Kolupaila's claim to the contrary, with the words: "The author is interested in Kolupaila's statement that the Manning coefficient n has no dimension. It has long been his belief that even in the metric system, in which this formula was derived, the coefficient was dimensionless; if dimensional homogeneity is maintained."

Whether or not the factor n has the same set of numerical values in the two different systems is actually no indication of its dimensional characteristics, for the apparent values of any such series can be changed at will merely by introducing a compensating coefficient. In the present instance this coefficient has been absorbed numerically by the coefficient K. On the other hand, whereas the dimension $L^{1/6}$ of the roughness measure actually belongs to both the compensating coefficient and the remaining factor together, from the mathematical point of view it matters little whether it is placed entirely with the one or the other. Kolupaila is right insofar as he says that its arbitrary retention by the factor n, when the latter's numerical values are held the same in both systems, leads to apparent anomalies in values of $R^{1/6}/n$ for data in the two systems. Nevertheless, the physical inconsistency of treating n as a pure number is apparently even more dangerous, because it leads to such errors [*Kolupaila*, 1955] as the plotting of the velocity ratio $V_{0.2}/V_{0.8}$ versus n alone; since the velocity ratio is a function solely of the resistance coefficient C [*Rouse*, 1946, pp. 197–200], this is tantamount to saying that the resistance coefficient depends upon the absolute rather than the relative roughness (that is, that C is independent of the depth of flow).

It is obvious that the source of the misunderstanding originally lay in the use of the same Kutter values in both the English and metric forms of the relationship, and that these values are now so much a part of engineering usage throughout the world that their proper conversion would no longer be acceptable. But it should also be apparent that, regardless of the actual numerical relationship between the roughness factor and the measurement in feet or in meters of the roughness that it characterizes, n must continue to be recognized in either system as an absolute (that is, dimensional) rather than a relative (that is, non-dimensional) roughness measure. Under these conditions it must be conceded to have the same dimension as the quantity to which it is related: length to the one-sixth power. The magnitude of the coefficient K will continue to depend upon the conversion of hydraulic radius and velocity from one system to another and the apparent lack of conversion of n; but the dimension of K must remain $L^{1/2}/T$ (that is, the same as that of $g^{1/2}$), however troublesome this may make the comparison of values of the non-dimensional ratio $R^{1/6}/n$ between systems.

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J. M. Robertson (University of Illinois, Urbana, Ill.; received Dec. 22, 1955)—Because of the almost universal acceptance of the Manning formula for open channel water flow, this review of the history leading to its present formulation is timely. For many years the numerical coefficient has been given as 1.486 implying an accuracy of one part in 1486 or 0.067 pct. As noted by Chow, this seeming precision must be blamed on the person who, in translating the constant (which was unity in metric units) to English units, did not consider significant figures. It is only in recent years that a few workers in this field have suggested calling the constant 1.49 as urged by Chow.

The writer concurs in the suggestion of simplifying the constant, but feels that Chow has not gone far enough. The constant should be written 1.5. This value is within one per cent of 1.486 and most calculations are of no greater precision. The value of unity for the constant in the formula in metric units certainly is not precise to one per cent. This fact is apparent whenever one searches for a suitable value of the roughness coefficient to introduce into the formula. Rarely, if ever, can this be chosen with a precision better than ten per cent. *Schoder* and *Dawson* (1934, p. 265) noted that the value of 1.5 was close enough for practical use, but elsewhere in their book wrote 1.486, as did all other books on hydraulics.

The matter of this numerical constant in Manning's formula is an example of the unscientific procedure of precise calculation being used to imply a higher precision than is justified by the basic in-

formation. It is strongly urged that those interested in open channel flow throw off the needless shackles and use Manning's formula as

$$V = (1.5/n)\ R^{2/3}\ S^{1/2}.$$

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James C. I. Dooge (Dept. of Civil Engineering, State University of Iowa, Iowa City, Iowa; received Dec. 27, 1955)—Chow's note on the Manning Formula prompts me to make the following comments which should be of interest to hydrologists in general. I will deal with two points only: Manning's early work on open channel flow and his ability as a hydrologist.

Manning entered the service of the Irish Office of Public Works in 1846 at the age of 30. He was engaged for the next few years on Drainage Schemes which were essentially Relief Schemes started during the years of the Great Famine. In 1851 he published a paper in the *Transactions* of the Institution of Civil Engineers of Ireland entitled Observations on Subjects connected with Arterial Drainage. This paper gives an excellent picture of the hydraulic equipment of the design engineer of a hundred years ago. In regard to open channel flow Manning suggests the following form of the Chezy formula as accurate enough for the design of natural channels

$$Q = 55A\sqrt{2FR}$$

where Q = discharge, cu ft/min

A = sectional area, sq ft
F = fall, ft/mile
R = hydraulic radius, ft

Manning published tables based on the logarithmic form of the preceding equation namely

$$\log Q = \log (55\sqrt{2F}) + \log (A\sqrt{R})$$

to facilitate computation. The tables covered falls from 0.1 to 20.9 ft/mile, bottom widths from 2 to 200 ft, and depths from 1 to 15 ft for trapezoidal channels with side slopes of vertical, 1:2, 1:1, 1.5:1, and 2:1. There were additional tables for special shapes of section and also for the calculation of the area and perimeter of sections not covered by the tables. The use of a single value of the Chezy C is understandable as, at that time, excavation in rock or boulders was completely uneconomical and hence natural channels would not vary very widely in roughness.

In this same paper Manning shows his ability as an hydrologist. The following quotation shows his grasp of essentials:

> "Absorption and evaporation, deductions for which are so necessary in calculating the mean discharge of a river, have little, if any, influence on the maximum discharge. For it is evident that there may be such a state of the atmosphere that no appreciable amount of evaporation may occur during the continuance of a flood, and no matter what may be the water-storing properties of the geological formation of the district, they may have been completely exhausted by previous rains; and, therefore, the maximum discharge will mainly depend upon the quantity of rain and the extent and comparative elevation of the catchment to the discharging channel."

This paragraph can stand without correction after a lapse of over one hundred years. Manning quotes observed flood flows as a guide to Irish conditions varying from 0.44 cu ft/min ac for 2,300,000 acres to 4.2 cu ft/min ac for 23,000 acres. Manning's practical ability in hydrology is revealed by a paper presented by him to the Institution of Civil Engineers (England) in 1866, which describes studies he made in connection with a proposed water supply for the City of Belfast. Manning erected three rain gages and two rectangular notches in the basin of 3400 acres and observed them for 12 months. He extended his rainfall record by comparison with the 14-year record at Queen's University, Belfast, nine miles away. Insisting that runoff was not a percentage of rainfall but a residual, he estimated the average monthly losses as follows

November–January	0.20	inches per month
February–April	0.40	inches per month
May–July	2.0	inches per month
August–October	2.8	inches per month
Annual loss	16.2	inches

He subtracted the average monthly loss for each month of the adjusted 14-year record of rainfall to get the mean monthly flow over 14 years; the losses were reduced in some cases so as to give a minimum monthly flow of 0.8 inches in the winter and 0.4 inches in the summer. In this Manning obtained a 14-year record of monthly flows as a basis for determining the required storage for the scheme.

In evidence before a Royal Commission about 1880, Manning estimated the maximum flow of a particular basin of 400,000 acres in the Irish Midlands as 400,000 cu ft/min but stated that as the flow would rarely exceed 350,000 cu ft/min, he would design for the latter figure. A 40-year record of gagings rated by current meter gives the maximum recorded flow of this basin as 370,000 cu ft/min.

Men like Robert Manning serve to remind us that in the past hydrologists were able to reach sound engineering conclusions without the use of slide rules, current meters, or tables of statistical functions. Manning was always eager to avail of the latest scientific knowledge and methods and in him these tools were allied with the disciplines of logical reasoning, common sense, and engineering judgment.

Ven Te Chow (University of Illinois, Urbana, Ill., Author's closure)—The author is indebted to the discussers for the additional historical information and the constructive comments on the numerical constant and the roughness coefficient of the Manning formula.

The historical accounts given by Rouse and Dooge are very valuable. One of the interesting facts thus revealed is that Manning was not only a hydraulician as generally accepted, but also a pioneer in hydrology.

The writer is glad to see that Rouse has the same understanding as the author by quoting, "What we now call the Manning formula was thus neither recommended nor even devised in full by Manning himself, whereas his actual recommendation recorded little further attention." Since *Gauckler* [1868] is quoted by Rouse, and Hagen by *Manning* [1891] for the early proposal and independent development of the formula, it should be interesting to know that *von Strickler* [1923] is believed also to have developed the formula independently but at a later date. Rouse's interpretation of the dimensional concept of the roughness coefficient is extremely illuminating and should be made known to all students in hydraulics.

The writer concurs with Robertson's further simplification of the numerical constant. Although he realizes the obstacle of human inertia and the tremendous effort required to revise the numerous tables and graphs of the Manning formula that have been published, the writer trusts that the human virtue of clinging to the rightfulness will eventually lead the way to a universal adoption of the simplified constant.

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"Discussion of Heated Precipitation-Gage Intake Tube"

F. C. ALLEN, R. E. GLOVER, W. U. GARSTKA, AND H. M. POSZ

[*Trans.*, **36**, 311–314, 1955]

Richard D. Tarble (U. S. Weather Bureau, College Station, Texas)—It is a recognized fact that under certain circumstances the standard precipitation gage is subject to capping by snow. While it is known that some record is lost due to capping, in most instances the only loss is the hourly distribution of precipitation as the cap melts into the gage following the storm. It should be pointed out that heated gages have been tested extensively by the Weather Bureau and other investigators and it is generally concluded that over an extended period evaporation losses were greater than losses from other sources [*Middleton* and *Spilhaus*, 1954]. Within a single storm or storm period, of course, possible evaporation losses might be negligible. No mention was made as to whether or not any test had been made on evaporation amounts in the gage.

One of the major influences on evaporation is heat. The principle of this gage is, of course, to supply enough heat to melt what snow might accumulate. The authors state that the heater is activated at a temperature of 45°F. This means that, during the winter rainy period, the heater would be in operation almost constantly during rain as well as snow storms. In addition, the heater would be in operation during clear cold days when no precipitation was occurring. It is suggested that a better operating temperature would be near 35°.

In another statement by the authors, they say that "the surface temperature of the intake tube

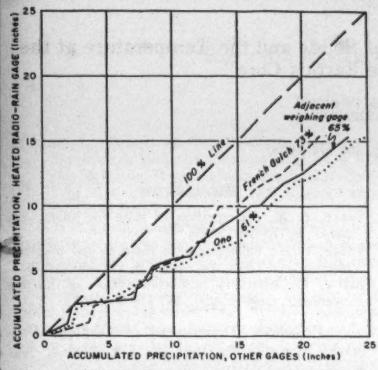

FIG. 3 – Clear Creek radio gage, elevation 2800 ft, 1953–54 season

will not exceed the temperature which occurs on a normal summer day." In the area where these gages operate, the normal July–August maximum temperature ranges between 85 and 100° with mean temperatures of 65–80°. Even this latter temperature seems excessively high for proper gage operation, and if adjustment is possible, as was indicated by the authors, it should be reduced considerably.

Another factor in the production of heat inside the gage is the black paint on the exterior.

During the period that the six gages have been in operation, a careful record has been kept of the daily accumulations. At each site, a shielded Friez weighing gage (non-heated) has also been in operation. A double mass plotting of the Clear Creek Friez record compared with the record from the heated gage is shown in Figure 3. Also plotted is the record from nearby Cooperative Observer stations. It was noted that the catch from the heated gages ranged from 56 to 76 pct of that measured by the Friez gage, and averaged 68 pct for the six gages in operation. This might be attributed to several causes in addition to evaporation. The non-standard shields that were installed on the heated gages originally were too light and were bent and distorted by the wind to such an extent that it could have influenced the catch. The gage itself is rather bulky, as may be noted in Fig. 1. This added bulk could conceivably create upward wind currents in the vicinity of the orifice of the gage to a greater degree than are present around the standard weighing gage. An updraft near the orifice reduces the catch. Heat from the vent could also create upward currents that would reduce the gage catch inasmuch as this vent is located close to the orifice itself.

The authors state that during the three-year operation of the gage "no accumulation of snow was observed either on the exterior or interior of the heated precipitation gage intake tube." However, the six experimental gages were located at elevations ranging from 2800 to 4000 ft and even the gage at the highest elevation is below the snow line in over 80 pct of the storms and the lower gages rarely receive snow. It seems that in order to test the gages adequately they should have been observed in an area where more snow occurs. It is not stated whether snow accumulated on the adjacent weighing gages.

One of the important uses to which precipitation record can be put is in relating it to annual streamflow as well as storm runoff. Due to sparse population and poor communications, very few gages have been established in the remote mountain regions of the West. It was hoped when these gages were first installed that they could be used to supplement what little seasonal data were available. The present schedule of operation calls for the activation of these gages between the months of November and April. This prevents the use of the gages in determining antecedent conditions as well as in obtaining an annual record, which means that valuable record from remote regions is not obtained.

The major advance made by this gage is not so much in overcoming the loss due to capping (this was apparently more than offset by the loss due to the influence of the shape of the gage, evaporation, and other factors inherent in the gage itself), but in providing a record that is immediately available from a remote region by means of radio. It is hoped that in the future, one of these gages can be tested in a higher region of the Sierra Nevada mountains where snowfall and subsequent capping is more of a problem than it is in the present location.

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Discussion of "Thermal Expansion of Solids and the Temperature at the Boundary of the Earth's Core"

JOHN VERHOOGEN

[*Trans.*, **36**, pp. 866–874, 1955]

P. E. Valle (Istituto Nazionale di Geofisica, Città Universitaria, Rome, Italy)—From the relation $(\partial K/\partial T)_V = 0$ Verhoogen has derived $(\partial K/\partial P)_T = -1$. This result is incorrect, because from the relations

$$\alpha K = \left(\frac{\partial S}{\partial V}\right)_T$$

$$\alpha V = -\left(\frac{\partial S}{\partial P}\right)_T$$

$$\left[\frac{\partial(\alpha K)}{\partial P}\right]_T = 0$$

We cannot derive

$$\alpha + V\left(\frac{\partial \alpha}{\partial V}\right)_T = 0$$

as Verhoogen has written. Using the classical theory of solids we find that the approximation

$$\left(\frac{\partial K}{\partial T}\right)_V = 0$$

is valid if the temperature is above the characteristic temperatures [*Valle*, 1953a]. Moreover, if the temperature is sufficiently high, we obtain

$$\left(\frac{\partial K}{\partial P}\right)_T = \frac{1}{3} + 2\Gamma\frac{\rho_0}{\rho}$$

where 2Γ is a positive constant of the order of some unities. For example at the top of D layer of the Earth's interior $2\Gamma = 3{,}2$ [*Valle* 1953b] so that

$$\left(\frac{\partial K}{\partial P}\right)_T = 3.53$$

This value is in excellent agreement with the results obtained by *Birch* [1952] from the theory of finite strain.

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VALLE, P. E., Sulle proprietà elastiche del mantello interno della Terra, *An. Geofis.*, **6**, 373–380, 1953b.

BIRCH, F., Elasticity and constitution of Earth's interior, *J. Geophys. Res.*, **57**, 227–286, 1952.

J. Verhoogen (Department of Geology, University of California, Berkeley 4, California, Author's closure)—Valle is correct in pointing out an error in the derivation of Eq. (8); the assumption that $(\partial K/\partial T)_V = 0$ does not imply $(\partial K/\partial P)_T = -1$. Yet it does imply that $(\partial \alpha K/\partial P)_T = 0$ which means that αK is a function of temperature alone.

This is sufficient to show that it is unlikely that K should be a function of V only, as suggested by Valle. Indeed, let $K = -V(\partial P/\partial V)_T = f(V)$. By simple integration we get

$$P = \phi(V) + \psi(T)$$

where $\phi(V) = -\int \frac{1}{V} f(V)\, dV$, and $\psi(T)$ is an arbitrary function of temperature. As αK is a function of T, say $\xi(T)$, α must be the product of a function of V and a function of T. Since $\alpha K = (\partial S/\partial V)_T$, S will be of the form

$$S = V\xi(T) + \zeta(T)$$

and relations of similar form could be derived for all other thermodynamic functions. To my knowledge, there is no experimental evidence that the variables T and V can be separated in such convenient fashion.

It had not previously occurred to me that Valle's treatment actually requires C_V = constant. Thus even if K should become a function of V only at sufficiently high temperature, it is unlikely that this condition would be satisfied in the Earth's mantle.

Reviews, Abstracts, and Bibliography

Reviews and Abstracts

CAHEN, L., *Géologie du Congo Belge* (preface by P. Fourmarier), Vaillant-Carmanne, Liège, xv + 577 pp., 98 figures, 36 photographs; fabricoid binding, 8.5 x 12 x 1.75 inches, 1954, 1200 Belgian francs (approximately $24.00).

It is with both pleasure and satisfaction that we welcome the appearance of a volume on the geology of the Belgian Congo; pleasure that such a volume is now available and satisfaction that it is an able, comprehensive work by an experienced geologist. The need for a book that would assemble the extensive geological knowledge of the Congo, obtained over the past century or more, has been felt for some time but even more keenly since the last war when attention was focussed on the country as a source of strategic materials.

Exploration of the Belgian Congo between 1866 and 1884 led to the formation of the Congo Free State in 1884–85 under King Leopold II, and later to Belgian sovereignty and status as a colony in 1908. Throughout the years since 1885, the extent of unexplored country and the large number of unsolved geological problems in the Congo, as compared to the small size of Belgium itself, have made it very natural, as Cahen himself says, for Belgian geologists to work there. Cahen is no exception and has spent altogether eleven years in Katanga, Lower Congo, and Kasai engaged in geological mapping and mining geology. Since 1947 he has been on the staff of the Musée Royal du Congo Belge in Tervuren, Belgium, where he has continued his work on the Belgian Congo. One knows, therefore, that this volume incorporates not only a thorough knowledge of the geological literature of the region, but also the perspective and interpretation that come from experience in the field.

The book comprises four parts which in all contain 20 chapters. Part I, with two chapters, briefly states the physiographic and geologic setting of the country and defines the methods and problems of stratigraphic terminology and correlation. Geologically, the Belgian Congo can be divided into two parts of very unequal size. One is the narrow strip of Mesozoic and Cenozoic marine sediments that forms the 25-mile coastline of the southwestern corner of the colony along the Atlantic. The other is all the rest of the country which can be divided into an area of sedimentary beds of Upper Paleozoic to Pleistocene age in the western portion, and the Basement Complex, chiefly Precambrian, that borders it on the northeast, east, southeast, and the extreme southwest.

Part II (chapters 3–10, 262 pages) deals with the geology of the Basement Complex. In the course of exploration, stratigraphic sections have been worked out for five areas: Katanga, Eastern Congo, Northern Congo, Western Congo, and Kasai-Lomami. The problem of correlation between these areas and with the bordering areas of Rhodesia, Uganda, and Tanganyika is a very real and difficult one, the solution of which requires the use of all possible tools. One of these is the application of radioactive age determinations.

Part III (chapters 11–18, 219 pages) describe the Paleozoic, Mesozoic, Tertiary, and Quaternary beds (La Couverture) that blanket the greater part of the Congo interior and also characterize the littoral region. Since 1930, remarkable progress has been made on the subdivision of these strata so that at the present time several series are recognized which previously were known only as Karroo and Kalahari. The recognition of an age difference between the upper part of the Karroo in the Belgian Congo and the Karroo of South Africa, together with the discovery of new fossiliferous beds, have emphasized the importance of retaining local names for many of these beds.

Part IV (chapters 19–20, 52 pages) describes the geologic occurrence of the mineral resources of the colony. The more important metals are copper, cobalt, uranium, gold, and tin. Diamonds are the chief nonmetallic product.

The volume closes with a two-part index. The first part is the usual alphabetic index which will be particularly useful in that the general area is given in parentheses for each local place name. The second part is an index of the chief mineral and fossil localities with latitude and longitude coordinates. The localities are distinguished by a difference in type style.

Cahen's book is written in a lucid and readable style. In the references given at the end of each chapter, the reader has the benefit of the author's familiarity with more than 2800 papers on the Belgian Congo. The sketch maps (both locality and geologic) and cross sections that accompany the text are neat, clear, and instructive. One should not criticize the omission of a detailed geologic map although it is a distinct lack. For those who are interested, a colored geologic map, in four sheets, on a scale of 1:2,000,000, by L. Cahen and J. Lepersonne, was published in 1951 by the Geological Commission of the Belgian Colonial Ministry. The photographs (many by the author and his colleague, J. Lepersonne) are well chosen and interesting. Both the style of type and the general make-up of the book lend themselves to easy reading and are certainly a credit to the publisher. Cahen's book will unquestionably make a name for itself, not alone for the enormous amount of information in it, but as the culmination of the excellent work of an untold number of geologists in unraveling the geological history of an area that is simultaneously exacting, puzzling, intriguing, and rewarding.

MARJORIE HOOKER

CAHEN, L., *Bibliographie Géologique du Congo Belge et du Ruanda-Urundi*, vol. I, 1818–1924, 175 pp., 1955; vol. II, 1925–1934, 188 pp., 1953; vol. III, 1935–1944, 131 pp., 1952; vol. IV, 1945–1954, 232 pp., 1955; published by the Musée Royal du Congo Belge, Tervuren, Belgium.

Using previous compilations by J. Cornet (1916) and A. Jamotte (1937, 1948, 1951), a complete bibliography of the geology and geophysics of the Belgian Congo for the years 1818–1954 has been assembled in four separate volumes as noted above. Volume V, 1955–1956, is in preparation. Vol. I contains 840 references; vol. II,

588; vol. III, 433; and vol. IV, 891. Altogether, including addenda and errata for previous volumes given in vol. IV, there are 2853 references with annotations in French. The references include not only those dealing specifically with the Belgian Congo, but also those of general nature based on specimens or material of Congo origin. Each reference is numbered, and the indexes refer to these numbers. The indexes are given in each volume and are given in two parts, geographic and subject. They are of necessity rather general. In vol. IV, for instance, the geographic index lists 22 areas and cross references eight others, and the subject index lists 28 headings and cross references 12 others.

MARJORIE HOOKER

LINSLEY, RAY K., JR., AND JOSEPH B. FRANZINI, *Elements of Hydraulic Engineering*, McGraw-Hill, xiii + 582 pp., 1955, $9.00.

The problems and illustrative examples in this book indicate that it may have been intended primarily as an engineering textbook, but a considerable portion of it is scientific, and in the opinion of this reviewer it is well deserving of attention from hydrologists and scientists in fields related to hydrology. This outstanding new book fills a definite need with its unique scope. It is characterized by excellent typography, clear and concise style, and logical presentation of the subject.

Part I, six chapters, consists of an analytical treatment of hydrology, organized on a subject-matter basis. The next seven chapters comprise Part II, which describes hydraulic structures and machinery. Part III, also mostly descriptive, deals with applications of hydraulic engineering, largely on a purpose basis. The scope of the book can conveniently be described by citing what it does not discuss: There is nothing on oil lines, hydraulic brakes or presses, cooling towers, fuel pumps, or cooling systems.

Chapter 1, Introduction, defines the scope of the book with a concise yet broad view of hydraulic engineering as seen by the authors. Chapter 2, Descriptive Hydrology, is an analytical treatment of measuring and giving areal significance to the main elements of the hydrologic cycle. Chapter 3, Quantitative Hydrology, includes precipitation-runoff relationships, hydrograph analysis including unit hydrographs, and storage routing. Negative local inflows are cited as errors, on page 61, with no reference to bank storage. Chapter 4, Groundwater, discusses its theoretical and practical aspects, including the development of wells. Chapter 5, Frequency Analysis in Hydrology, includes a few items that statisticians might object to. One is the use of N in the formula for recurrence interval. Another item is the use of N, instead of $N - 1$, for standard deviation on page 103. Figure 5–9 presents a novel analysis which would have some obvious and serious limitations if applied to a set of very many stations. Chapter 6, Water Law, is thoughtful, and excellent as far as this reviewer is qualified to say.

Chapter 7 (the first of Part II), Reservoirs, discusses their physical characteristics, functions, sedimentation and sediment transport, and waves. With the subject matter of Parts II and III divided largely on the basis of relatively few major subjects, it must have been a difficult decision to include sediment transport under the subject of reservoirs instead of discussing it under the subject of open channels or river modification. Chapter 8, Dams, includes a brief discussion of their engineering design and construction by type of dam: gravity, arch, earth-fill, etc. The spalling of concrete when subjected to alternate freezing and thawing is given as a reason for avoiding thin arch or buttress dams in extremely cold regions. Chapter 9, Spillways, Gates, and Outlet Works, describes these appurtenances in a comprehensive and clear, yet concise manner. Chapter 10, Open Channels, includes development and application of pertinent hydraulic principles to engineering problems of open channel flow. There is a refreshing use of 1.49 instead of 1.486 in the Manning formula. (Will 1.5 ever be used?) The chapter describes methods for measuring flow. Chapter 11, Pressure Conduits, includes excellent treatment of earth loads on buried pipe, water hammer, surge tanks, valves, strength and durability of materials of construction, as well as theory and measurement of flow for various pipe systems. Chapter 12, Hydraulic Machinery, presents the theory and practical aspects of many kinds of turbines and pumps. Chapter 13, Some Economic Aspects of Hydraulic Projects, was written by E. L. Grant. There are minor inconsistencies between the durability of some of the materials as given in Table 13-2 (concrete pipe, 20 years), and in Chapter 11, page 284 (concrete pipe, 50 years).

Chapter 14 (the first in Part III), Irrigation, includes water requirements of plants; soil-water relationships; and measurement, quantity and methods of applying irrigation water. Table 14-3, subject to quibble, gives a convenient indication of the moisture capacity of various types of soil. Chapter 15, Water Supply and Purification, discusses methods for estimating demand, and describes distribution and purification methods. On page 378, freezing depths could well have been discussed in a more quantitative manner. There is good brief reference to cross connections. In the discussion of treatment of water there is no reference to the modern practice of adding lime where necessary to control acidity and corrosion. On page 396 appears a statement: "Microscopic organisms called plankton, which include algae, protozoa, rotifers, and crustaceans, are found. . . ." This is one of the few examples of any but the most precise and careful writing in the book. On page 397 it is stated with unnecessary caution that sufficient cooling may freeze water. Chapter 16, Hydroelectric Power, discusses economic considerations, and design and operation of systems and components. At the beginning of section 16-3 it is said that 'some' systems are interconnected. A better statement appears at the top of page 557. Chapter 17, River Navigation, includes discussion of channel modification, and locks and dams. Chapter 18, Drainage, includes municipal storm drainage, drainage of agricultural land, and highway drainage. In Figure 18-3, the types of inlets are shown erroneously with interchanged Sections and Plans. In Figure 18-24b the fill seems to intersect the backwall too high to prevent scour around the inlet. The drawing might be enhanced by showing one or two seepage cutoff collars. Chapter 19, Sewerage and Sewage Treatment, covers its subject well. On page 492 the depth of sewer is given as a function of elevations of connections and magnitudes of superimposed loads, with no reference to frost depths. Chapter 20, Flood Control, is thoughtful, up-to-date, and excellent. In the discussion of floodways, diversion downstream rather than upstream from major cities is advocated, in spite of the by-pass systems cited for Sacramento and New Orleans. On page 549, the diagram and accompanying text lets the reader infer that

reservoirs and levees cost and have the same effects jointly as each alone. Chapter 21, Multiple-Purpose Projects, discusses the problems of coordinating competing functions, and related topics. At the top of page 557, it would have been pertinent to cite a main requirement of power: uniform high head.

The book has a useful appendix of physical constants, conversion tables, etc., and eight pages of subject index. In the beginning of the book there is a helpful list of symbols and abbreviations.

WALTER T. WILSON

KIRKALDY, J. F., *General Principles of Geology*, Philosophical Library, New York, 327 pp., 6 plates, 82 figures, 1955.

This book is unusual in the wide coverage of geology which it presents. The greatest emphasis is on what is commonly termed 'hard-rock' geology. This consists of 120 pages of crystallography, mineralogy, petrology, and petrogenesis, and 16 pages of economic geology. General and physical geology is covered in 120 pages, and historical geology in 50 pages. There are two appendices. Appendix 1 treats the interpretation of geological maps in 11 pages. Appendix 2 lists suggested books for further reading.

The wide coverage of geology included results in much condensation of the material. In some parts the book appears to be like an encyclopedia or a scientific dictionary. This leads to an uneveness of treatment. The illustrations are chiefly from British sources.

The book is designed for elementary courses.

GEORGE T. FAUST

Abstracts of the papers presented at the Thirty-seventh Annual Meeting, Washington, D. C., April 26–May 4, 1956 listed in the order of the last name of the first author

WILLIAM C. ACKERMANN (Head, Watershed Hydrology, Plant Industry Station, Beltsville, Md.) *Needed Research in Sedimentation*. All phases of sedimentation are greatly in need of expanded research. This includes the processes of entrainment, transportation, and depositon. Understanding of the applicable fundamental laws has become more urgent since a rapid increase in watershed and channel works has changed the natural regimen of many streams. Research should include improved techniques of measurement as well as laboratory and field studies.

L. T. ALDRICH, G. W. WETHERILL, G. R. TILTON, and G. L. DAVIS (Carnegie Institution of Washington, Washington, D. C.) *Comparisons of Rb-Sr Ages with Concordant U-Pb Ages of Pegmatites*. Rb-Sr ages of micas and feldspars have been compared with concordant U-Pb ages of uraninites from six pegmatites. The U-Pb age of the pegmatites ranges from 375 to 2700 million years. The Rb-Sr age was found to be consistent among the minerals from the same pegmatite. Using any one published half-life for Rb^{87} to calculate the Rb-Sr age, the ratio of the Rb-Sr age to the U-Pb age is a constant. The Rb-Sr ages of micas and microclines calculated for a Rb^{87} half-life of 5.0×10^{10} years compared with the concordant uranium ages in the same pegmatites are:

Location	Mineral	Rb-Sr age	U-Pb age
		m y	m y
Bikita, S. Rhodesia	Lepidolite	2680 ± 100	2650 ± 100
Viking Lake, Sask.	Biotite-chlorite	1880 ± 100	1890 ± 50
Ingersoll Mine, S. Dak.	Lepidolite	1680 ± 75	1600 ± 50
	Muscovite	1730 ± 75	...
	Microcline	1600 ± 75	...
Cardiff Twp., Ontario	Muscovite	990 ± 50	1020 ± 30
Wilberforce, Ontario	Biotite	990 ± 50	1030 ± 30
Chestnut Flat Mine, N. C.	Muscovite	370 ± 15	...
	Microcline	385 ± 15	375 ± 10

The Rb-Sr ages are seen to be consistent with the uraninite ages over a range in age of almost a factor of ten.

D. W. ALLAN AND J. A. JACOBS (University of Toronto, Toronto, Canada) *Initial Thermal Conditions in the Solar System*. The objects comprising the solar system presumably had a common origin, and therefore the examination of possible initial conditions and consequent thermal histories for such bodies as the asteroids and the Moon provide important evidence on the initial state of the Earth. The results of recent studies by the authors of the thermal history of asteroids and the origin of meteorites and of the thermal history of the Moon are discussed and related to the even more difficult question of the Earth's initial thermal state.

L. P. ALLEN (WMAL Radio and Television, Washington, D. C.) *Semantics and Communications*. Introduction of the problem of semantics in the communication of weather information and the exploration of the role this obstacle plays in the dissemination of weather. Some consideration will also be given to phonetics.

HENRY W. ANDERSON (California Forest and Range Experiment Station, Berkeley 1, Calif.) *Relating Sediment Yield to Watershed Variables*. The yield of sediment from watersheds varies with three sets of factors: (1) inherent watershed characteristics such as geology and topography; (2) conditions of watershed, vegetation, and land use; and (3) nature of storms and streamflow which produce and transport sediment. The determination of yield depends also on the sediment measuring device and on which fraction of total sediment yield is measured. These sources of variation can be evaluated by study of the yield from many watersheds which have wide variations in these factors. Such studies are useful to determine and evaluate the principal sources of sediment, to evaluate the probable effects of conservation programs on yield, and to provide criteria for design of reservoirs and channels. This paper summarizes some recent studies in which multiple regression analysis was used in relating sediment yield to watershed variables. These studies are discussed in the light of methods of selecting watersheds, data, variables, and functions; and the effects of neglected variables, errors in variables, and exclusion of non-significant variables.

G. L. ARNOLD (Lockheed Aircraft Corp., Burbank, Calif.) *A Graphical Method of Interpreting Refractive-Index Profiles in Terms of Air-to-Air Radar Coverage.* An attempt has been made to simplify operational forcasting of air-to-air radar coverage, given the refractive-index profile. Current methods of ray tracing require equipment usually not available for routine operational use. Two graphs have been developed: one to forecast the distance to the radio hole and the other to forecast the width of the radio hole. These graphs allow the use of continuous values for search height, target height, duct height, duct thickness, and duct intensity.

T. S. AUSTIN, E. D. STROUP, AND M. O. RINKEL (U. S. Fish and Wildlife Service, Honolulu, T. H.) *Variations in the Equatorial Countercurrent in the Central Pacific.* Data were analyzed from MV *Hugh M. Smith*, Cruise 15, consisting of four consecutive transects of oceanographic stations along 140° W between 8° N and 7° S. The results showed that during a five-week period the maximum eastward velocities in the Countercurrent progressively increased from 63 to 120 cm/sec and the volume of flow increased from 18 to 22 $\times$ 10^8 m^3. In spite of these short-term variations, these observations, when considered along with data from many other POFI cruises, show that in the central Pacific the Equatorial Countercurrent is remarkably predictable in latitude and general physical characteristics.

PAULINE M. AUSTIN (Massachusetts Institute of Technology, Cambridge, Mass.) *Applications of the Radar as a Meteorological Instrument.* The radar was first developed as a detection device, and its major application to meteorological observations has been in that capacity. Within the limitations set by radar range, resolution, etc., the radar shows the extent, pattern, development, and motion of precipitation areas in three dimensions. This information, as an interpolation in space and time to the regular synoptic data, is useful to the forecaster. It has proven to be especially valuable in the observation and tracking of severe storms such as squall lines and hurricanes. Applications of radar observations to synoptic meteorology also include the determination of statistical relationships between the small-scale (mesometeorological) characteristics of precipitation and synoptic parameters. Additional instrumentation designed especially for weather radar studies permits the measurement of the average intensity of the signal from the precipitation in a selected region. Measurements of the depolarization, a function of the shape of the precipitation particles, and of the signal fluctuation rate, which depends upon the motion of the particles, can also be made. A brief discussion of the applications of these measurements to the study of precipitation physics and small-scale atmospheric circulation is included. Consideration is also given to the advantages and limitations of the radar as an instrument for measuring rainfall amounts.

SUMNER BARTON (The Boston Globe, Boston, Mass.) *Confusion Must Be Eliminated in Weather Warnings.* A leading meteorologist recently said: "A warning is as good as a forecast." That is not always true. A warning picks up where a forecast leaves off and only through a clarity in meaning at the forecasting source can newspapers or other media relay the warning. This admittedly is a complex problem, but some measures can be taken to reduce public confusion by altering some warning systems, particularly for hurricanes, and by attempting to eliminate other loose terminology. A warning defeats itself if people are confused.

ROBERT T. BEAUMONT (209 S.W. 5th Ave., Ross Bldg., Portland 4, Ore.) *A Criterion for Selection of Length of Record for a Moving Arithmetic Mean for Hydrologic Data.* In hydrologic work a reliable base period is usually needed for reference. A procedure has been derived by which an objective selection as to the best length of record can be made for computation of a moving arithmetic mean. Results are given for several records of precipitation and runoff at stations in the western United States.

H. A. BEDIENT AND G. P. CRESSMAN (Joint Numerical Weather Prediction Unit, Washington 25, D. C.) *Automatic Data Processing for Numerical Weather Prediction.* The experience of the Joint Numerical Weather Prediction Unit (JNWP) in developing an automatic data-processing system is described. The problems encountered and the requirements of JNWP for a more efficient and specialized international data-distribution system are discussed. The present problems encountered by JNWP include the necessity of receiving large amounts of all types of data in order to obtain a relatively small volume of useful upper-air data, special regional and national varieties of CSM Code forms, frequent incorrect use of code forms, near ambiguities in codes, and the use of plain language mixed with coded messages. The requirements of JNWP are for high-priority transmission of selected level upper-air data from most of the northern hemisphere in standardized and abbreviated form. Complete reporting from the net is desired. The messages should contain internal checks which are independent of the hydrostatic equation.

PAUL C. BENEDICT (U. S. Geological Survey, 510 Rudge-Guenzel Bldg., Lincoln, Nebr.) *Fluvial Transportation of Sediment.* Developments that have been made in sediment transport concepts, which are particularly pertinent to the symposium on sediment yield, are outlined. Modes of sediment transport are described. Theories of the vertical distribution of suspended sediment in the stream cross-section are summarized. The interrelations of concentration gradients with high sediment concentrations, velocity gradients, exchange coefficients, bed roughness, and contact load are mentioned. The Einstein method for computing bed-material load has led to a modified method by which total sediment load may be computed; the agreement of computed loads with measured loads at an artificial turbulence flume on the Middle Loup River and at a natural chute on the Niobrara River is shown to be good. The effects of total sediment load on stream characteristics are illustrated.

STUART G. BIGLER (Texas A and M College, College Station, Texas) *The Use of Television for Local Dissemination of Radar Observations to the Public.* A method for giving more precise information to the public on expected periods of severe local storms through the use of current radar pictures is presented. Suggested methods of transmitting the picture to the television studio, and methods, frequency, and length of presentation are described. Some examples taken from film files are presented.

HARRY F. BLANEY (Western Soil and Water Management Section, Soil and Water Conservation Research Branch, Agricultural Research Service, Los

Angeles, Calif.) *Evaporation Study at Silver Lake in the Mojave Desert.* Silver Lake was formed within a period of three days as a result of a flood in the Mojave River in March. Previously the Lake had been dry for several years. Its maximum size was seven miles long and two miles wide. No inflow or outflow occurred during the study and the Lake was entirely dry at the end of the following year. Borings in the tight clay lake bottom indicated there were no losses by seepage. The purpose of the study was to determine coefficients for converting pan evaporation to lake evaporation and to develop an empirical relation between evaporation and meteorological factors under desert conditions. Daily observations were made for about a year of temperature, humidity, wind movement, precipitation, and pan evaporation at a Class A Weather Bureau Evaporation Station, and of changes in water level and temperature of the Lake. This paper presents a summary of these measurements. The results show that annual evaporation from Silver Lake was 79 inches and that a coefficient of 0.60 should be used in reducing Weather Bureau pan evaporation to lake evaporation in desert areas.

G. H. Bolt and R. D. Miller (Dept. of Agronomy, Cornell University, Ithaca, N. Y.) *Calculation of Total and Component Potentials of Water in Soil.* In principle, the physical state of water present in porous media may be described macroscopically in terms of the total potential or microscopically in terms of component potentials. These may take into account position in the Earth's gravitational field, pressure, solutes, and interfacial (adsorption) phenomena. The success of recent tests of the Gouy-Chapman theory of the electrical double layer for silicate clays apparently provide a sound basis for analysis of adsorption phenomena in mineral soils. According to this theory, the 'adsorption' of water by clay minerals is in part a manifestation of the concentration of ions present in the electrical double layer and in part due to the interaction with the intense electrical fields present in this region. Analytical expressions and appropriate curves are presented which describe the component potentials on a microscopic basis and the total potential on a macroscopic basis according to the Gouy model of the double layer for systems in which the total solutes remain constant or in which the concentration of the equilibrium dialyzate remains constant. These results are compared with appropriate data selected from the literature.

M. C. Boyer (Meadowbrook, Apt. 217, 3412 Adams Court South, Indianapolis, Ind.) *A Correlation of the Characteristics of Great Storms.* The three characteristics of a storm are the maximum precipitation at the center or eye, the duration of the storm rainfall, and the areal extent. These are generally presented graphically by means of curves of relation between average precipitation and area, determined by volumetric integration outward along curves of equal total rainfall, or isohyets. Each storm has a characteristic depth-area-duration curve, and storms cannot be effectively compared on this basis because of the wide variation in their areal extent. This paper presents a method whereby storms may be compared by means of a mathematical correlation of the three characteristics, regardless of the area covered by the storm. It was assumed that: (1) The distribution of precipitation outward from the eye of a storm follows the exponential relation $P = P_{\max} e^{-aL}$, in which P is the precipitation along any isohyetal of the storm, $P_{\max}$ is the maximum precipitation at the eye of the storm, e is the base of Naperian logarithms, a is a coefficient of distribution, and L is the distance from the eye to the isohyetal, measured along an axis of the storm. (2) The isohyetals are geometrically similar, so that the area A enclosed by any one is related to the length L by $L = kA^{0.5}$. (3) A characteristic area may be selected for each storm so that the depth-area curves may be reduced to dimensionless terms. The area chosen is that for the isohyetal which encloses that part of the storm whose average precipitation is one-half the maximum. These assumptions are combined mathematically into

$$P_A/P_M = \frac{1.69}{A/A_{.5}} \left[1 - e^{-1.09(A/A_{.5})^{0.5}}(1.09A/A_{.5})^{0.5} + 1)\right]$$

The validity of this equation was investigated by a study of a number of great storms that have occurred over the central Mississippi Valley. The results were found to be satisfactory and curves of relation between depth, area, and maximum precipitation for durations of 6, 12, 24, and 48 hours were prepared. From the data presented regular storm patterns may be prepared for the determination of maximum floods in the design of flood-control works in the central United States.

Dorothy L. Bradbury (University of Chicago, Ill.) *An Experiment in Stability and Moisture Analysis.* A detailed analysis of the storm of March 20–22, 1955 was made in order to study the relationship between the observed patterns of clouds and precipitation and those of static stability, water-vapor content, and isallabaric gradients. An attempt was made to determine the net convergence of water vapor into the area occupied by the storm and to compare the amounts of such convergence with the mean precipitation over the area.

Max C. Brewer (Geophysics Branch, U. S. Geological Survey, Menlo Park, Calif.) *The Thermal Regime in Arctic Lakes.* Much of the Arctic coastal plain in Alaska is covered by shallow lakes. Those in the Barrow area, which are believed to be representative of most of the lakes in the coastal plain, generally seem to be either 2 to 3 feet or 6 to 9 feet deep. The shallow lakes can often provide a suitable summer water supply, but only the deeper lakes provide a significant water supply throughout the year.

The water in the individual lakes is essentially isothermal during the ice-free period which lasts from late June until September. The maximum temperature recorded in a lake near Barrow in 1954 was about 12°C. When ice formation begins, the temperatures of the body of water as a whole may be only a few tenths of a degree Centrigrade above zero. Once the lake surface is iced over, the bottom and near-bottom water temperatures may rise as much as two degrees Centigrade. The magnitude of the rise and the time over which the rise takes place depends on the distance from shore and the depth of water. A gradual cooling then takes place during the balance of the winter. Permafrost underlies the shallow lakes but an unfrozen basin several hundred feet deep may extend beneath the deeper lakes.

J. C. Brice (Dept. of Geology, Washington Univer-

sity, St. Louis, Mo.) *Erosion by Terracettes on Loess-Mantled Slopes.* Terracettes that consist of sod-covered treads and bare risers appear in many places on the loess-mantled slopes of southern Nebraska. Such terracettes have been attributed to slump movement resulting from slippage of individual blocks along deep-seated surfaces or along vertical joint planes. Field evidence in the Medicine Creek drainage basin indicates that the terracettes there have originated from breaks in the sod cover that initiated upslope scarp retreat. Abundance and growth of terracettes are related to thickness of the sod cover and to the slope angle on which they are developed. An understanding of the origin of terracettes is necessary for their prevention and control and for making quantitative estimates of their sediment contribution.

G. W. Brier (U. S. Weather Bureau, Washington 25, D. C.) *The Effect of Errors in Estimating Probabilities on the Usefulness of Probability Forecasts.* Objections to the use of probability forecasts have been made on the basis that no methods are available for making such forecasts or that estimates of probabilities from finite samples are not accurate enough for practical purposes. A quantitative analysis indicates small or even moderate errors in estimating probabilities have no appreciable effect on the usefulness of probability forecasts. It is found that the conditions under which probability forecasts are useful for particular operations can be determined easily if certain data are available.

Wallace S. Broecker (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *C^{14} Dating of the Wisconsin-Recent Climatic Change from Ocean Floor Sediments.* C^{14} measurements on cores from the Atlantic and Caribbean indicate that the Wisconsin-Recent climatic change identified by foraminifera and paleotemperature studies occurs rather sharply about 11,000 years ago. Measurements have been made on cores containing sediments formed under a wide variety of conditions and possible sources of error have been examined. The reason for the 3000–5000 year dates at the top of the cores appears to be due mainly to a rapid decrease in sedimentation rate in post-glacial time rather than the inclusion of older carbonate. A sequence of eight dates on one core taken on a rise in the equatorial Atlantic, where evidence indicates the absence of slumping or other abnormal deposition, shows that the rate of sedimentation during the Wisconsin was rather uniform, increased just prior to 11,000 years ago, and then decreased sharply toward the present.

Irene Browne and A. P. Crary (Air Force Cambridge Research Center, Cambridge, Mass.) *Arctic Ice-Pack-Movement Studies.* A study of the movements of the ice island T-3 during the period April 1952 to May 1954 is presented. Plots of deviation angle and ratio of ice to wind movements with wind speeds for nearly 100 segments of nearly constant winds and well-established locations show a considerable amount of scattering. The general average of these data is compared with estimates of the steady-state forces: wind drag, water drag, and Coreolis force. The effect of ice continuity over large areas is shown to contribute little to the general scattering of data. With available information of sea-level slopes from bubble-level readings, and of compensating currents from drag-meter observations, an attempt is made to correlate the data with the type of surface-pressure systems present.

Ivan W. Brunk (U. S. Weather Bureau, Chicago, Ill.) *Automatic Distribution of Weather Information and Forecasts.* Operation of an office, the primary function of which is the distribution of weather forecasts and information, will be described. Problems related to taking care of the needs of the general public, press associations, newspapers, and radio and TV stations will be discussed. Various automatic distribution methods which are used will be described, including telephone, teletypewriter, telegraph, and radio. Mention will be made also of additional automatic methods which could be utilized.

Perry Byerly and John DeNoyer (University of California, Berkeley 4, Calif.) *Energy in Earthquakes Computed from Geodetic Observations.* If the strain in the rock just before faulting is entirely shear, the strain energy may be written as

$$E = (\mu/2) \iiint f^2 \, dx \, dy \, dz$$

where f represents the strain as a function of the coordinates. For a vertical fault, take x and y in the Earth's surface with y along the fault trace. Take z vertical. From displacements measured by surveys before and after three shocks in which surface faulting was observed, we find that the components of displacement due to strain may be expressed in the form

$$C = C_{\max}/2 - A \tan^{-1} ax$$

and the components of strain as

$$\phi = -aA/(1 + a^2 x^2)$$

a and A being constants. These forms may be multiplied by $1 - y/L$ if the data suggest a dying off of displacement along the fault. The energies so computed for the San Francisco (1906), the Imperial Valley (1940), and the Dixie Valley-Fairview Peak (1954) shocks agree in order with those computed from the Richter-Gutenberg magnitude-energy formula.

G. D. Cartwright (U. S. Weather Bureau, Washington 25, D. C.) *Utilization of Non-Standard Observations.* For nearly 100 years, much of the effort of international collaboration in meteorology has been to achieve standardization of data interchanged between countries for analysis and forecasting purposes. A growing variety of observational data, new and more powerful analytical tools, and new requirements for meteorological analyses and forecasts are rapidly changing this situation. Measurements of radio refractive index, radar echoes, ionospheric observations, a variety of geophysical measurements, and, ultimately, measurements from an Earth satellite all have meteorological implications of some degree. A list of possible types of non-standard observations is presented with suggestions as to the operational units needed for the collection of these data and their integration into the system. The impact of these developments in analysis and observation on present practices are discussed in relation to large-scale phenomena as well as to local forecasting. The use of non-standard data in different kinds of meteorological situations and by various classes of offices is reviewed. The problem of 'conversion' of implicit data to explicit form, for example, changes in refractive index to corresponding changes in the temperature or moisture gradients, is discussed

and several possible solutions examined. The effects of these on transmission systems and the design of new systems more suited to this purpose are suggested.

GORDON D. CARTWRIGHT AND VAUGHN D. ROCKNEY (U. S. Weather Bureau, Washington 25, D.C.) *Radiosonde Observations Aboard Merchant-Type Vessels.* An expansion of experimental radiosonde observational programs aboard merchant-type vessels, that were reported in 1953, is described. Observational problems and results aboard such varied types of vessels as naval transports, tankers, freighters, and ore carriers, operating in the Atlantic and Pacific Oceans and the Gulf of Mexico, are described.

EDWIN J. CHERNOSKY (Ionospheric Physics Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Mass.) *The Delta Measure of Geomagnetic Activity.* It is proposed to measure geomagnetic activity by determining the average arithmetic rate-of-change of components of the Earth's field. This is done for available reduced data by computing the differences between consecutive hourly values of horizontal intensity and averaging these differences for each day to give ΔH_1. Similar computations are made to give ΔH_2 from moving bihourly means instead of the hourly means. Computations with moving six-hourly mean values give ΔH_6 and so forth. From an appropriate series of such daily ΔH indices a rate-of-change spectrum can be derived which is somewhat comparable to a frequency spectrum. Other field components can be used to compute ΔZ, ΔF, etc. By providing what may be considered a 'frequency spectrum' the delta measure makes a systematic survey of geomagnetic (or other) variations possible. An exploratory study is being undertaken of the indications given by the measure and some comparisons made with existing indices.

FRANK CHEW (Marine Laboratory, University of Miami, Coral Gables, Fla.) *A Study of Transverse Motion in the Florida Current.* A study of the nonperiodic transverse motion in the Florida Current off Miami is made by two sets of specially paired hydrographic sections and by the average surface current as determined by numerous GEK fixes. It is suggested that the transverse motion can be largely explained as the result of diffusion of momentum from the current core.

BERNARD CHOVITZ AND IRENE FISCHER (Army Map Service, Washington 25, D. C.) *A New Determination of the Figure of the Earth from Arcs.* As part of a broader study on the figure of the Earth, a tentative size is derived, based on four arcs: a meridional arc extending from South Africa to Scandinavia, a meridional arc extending from Chile to Canada, a parallel traversing the United States, and a parallel extending from western Europe to Siberia. The first two arcs were completed within the past three years and are the longest of their kind ever available—about 100° in length. The information they supply on the Earth's size is presented here for the first time.

The data were applied in two forms: astrogeodetic (free-air), and isostatically reduced deflections. The solutions assumed a flattening, $f = 1/(297 \pm 1)$. The following values were obtained for the semi-major axis,, a: free-air, 6,378,240 $\pm$ 100 meters; and isostatic, 6,378,285 $\pm$ 100 meters. As a single value, 6,378,260 can be taken. The uncertainty of a is due not only to the data, but also in large measure to the assumed uncertainty in f, and to an uncertainty due to the systematic undulations of the geoid as given by Jeffreys.

E. J. CHRISTIE (U. S. Weather Bureau, New York, N. Y.) *Some Problems of Practical Meteorology.* The problems surrounding the formulation and dissemination of weather forecasts are numerous and varied. They very probably could be put into two main classes: those involved with the science of meteorology itself, and those which come about in the process of dissemination of weather information. To the practical meteorologist, the one charged with the responsibility of providing a weather service to a local community, the problems which come about in the program for the distribution of weather forecasts, advisories, and other data become as great as, or greater than, those inherent in the science itself. Even such a well-known term as 'fair' may have a different connotation to a user of weather information than it does to the forecaster. A mere mention of the word 'hurricane' strikes fear in the minds of some, while others who have learned more about the behavior of these weather phenomena carry on and make plans to meet any eventuality. Difficulties arise frequently from the lack of 'know how' on the part of the user of weather information and it would appear that each individual or each agency which has need for a weather service would do well to follow three simple steps toward developing a good weather program: (1) Survey operations to determine as exactly as possible how weather affects them. (2) Find out what can reasonably be expected of the science of meteorology and where and how weather information can be obtained. (3) Coordinate the two into a working program.

JOHN F. CLARK (Naval Research Laboratory, Washington 25, D. C., and University of Maryland, College Park, Md.) *The Distribution of Electric Field, Potential, and Space Charge in the Troposphere.* A P4Y aircraft has been instrumented to measure potential gradient simultaneously with other atmospheric-electric and meteorological parameters. More than 20 flights have been made during fair weather at altitudes up to 20,000 ft over many land and sea areas in the northern part of the western hemisphere. The measured electric field has been corrected for the distortion of the aircraft itself by comparing observed values of field and conductivity on the surface and at altitude during low-altitude flights over a portable ground station. The fair-weather atmospheric potential and space-charge density are derived from the altitude distribution of the potential gradient. The altitude and geographic dependence of these quantities is presented and interpreted. The diurnal variation of these quantities over Greenland is also discussed.

JOHN F. CLARK AND JAMES H. KRAAKEVIK (Naval Research Laboratory, Washington 25, D. C., and University of Maryland, College Park, Md.) *Airborne Atmospheric-Electric Studies of Radioactive Contamination.* A P4Y aircraft has been used to measure atmospheric potential gradient and both polar conductivities over Virginia in the vicinity of radioactive debris from the Nevada burst No. 3 of March 1, 1955. Typical fair-weather altitude distributions of atmospheric conductivity, electric field, conduction current, potential, and columnar resistance were obtained from ground level to 20,000 ft during a flight on March 2, prior to the arrival of the radioactive contamination in the Virginia area. A second flight on March 3 between

04h 00m and 07h 00m GMT included a penetration of the radioactive cloud at a 20,000-ft altitude, directly above its 06h 00m position along the 18,000-ft estimated trajectory. At the point of maximum penetration, the total conductivity was 41×10^{-14} mhos per meter, which is over 60 pct greater than the value recorded on the previous day at that altitude, and 25 pct greater than the highest conductivity recorded elsewhere at 20,000 ft during some 25 flights scattered over an area from 50° to 120° W longitude and 30° to 67° N latitude. The potential gradient within the radioactive contamination varied in inverse proportion to the conductivity, maintaining the conduction current sensibly constant. Application of the ionization equilibrium condition under the assumption of zero large-ion density yields a minimum increase in ionizing radiation in the cloud of 2.6 times the cosmic-ray background.

J. B. COCHRAN (Captain, U. S. Navy Hydrographic Office, Washington 25, D. C.) *U. S. Navy Hydrographic Office Contributions to Our Knowledge of Antarctica.* As during past cruises by the U. S. Navy to Antarctica, the U. S. Navy Hydrographic Office actively participated in charting the coastline and adjacent waters of this continent during the recently completed Operation Deepfreeze. Hydrographic and oceanographic results to date are outlined.

ALBERT E. COLDWELL (Tulsa District, Corps of Engineers, Tulsa, Okla.) *Importance of Channel Erosion as a Source of Sediment.* A specific statement is not possible as to the percentage of total erosion caused by channel erosion. Watersheds containing tight soil may be almost entirely free of gullies; streams may have deep and narrow channels with stable banks; and slopes may be small, resulting in little bed movement. On the other hand, watersheds draining upland sandy areas may have many gullies with rapid headward movement; channels may be shallow and wide, with such widening actively increasing at the present time; and steep slopes may cause a considerable amount of bed movement. Combinations of these factors may occur in a single watershed. Absence of sediment measuring stations on gullies make volumetric estimates based on rate of change in depth, width, and headward movement necessary. Establishment of valley and channel range profiles is helpful in estimating bank erosion. It is being found that aerial photographs taken some years apart indicate that bank erosion may cause a greater part of the erosion in a watershed than was previously supposed. Confirmation of this is indicated by relatively permanent shifts in discharge rating curves. For bed movement, reliance must be placed on current research and established formulas.

MILTON E. COMPTON (Berg, Hedstrom and Co., 1170 Broadway, New York 1, N. Y.) *Geodetic Distances with Geodimeters.* A family of geodimeters for precise geodetic distances has been established. The highly accurate Model 1 in use by many countries has been redesigned and replaced by the even more accurate Model 2. The Model 2 has an instrumental uncertainty of less than ten millimeters, and a maximum range exceeding 30 miles. For the first time 'first-order' base lines are available to the geodesist in quantity and speed with a minimum manpower requirement. The latest addition to the geodimeter family is the Model 3 with an instrumental uncertainty of less than ten centimeters. The Model 3 is light and portable, and can be used for lower-order base lines, traverse, and triangulation arcs. Geodetic trilateration with as little effort as angular measurements is now possible. A general discussion of the instruments, their design considerations, and the utilization of physical phenomena to the degree required for the stated accuracy is presented.

JOHN C. COOK (Southwest Research Center, San Antonio, Texas) *Some Observations in a Northwest Greenland Crevasse.* A particular crevasse was entered frequently over a period of two months during the summer of 1955. The interior was measured, sketched, and photographed. Marked changes in the height of the bottom water level with weather were noted. Analogies to karst drainage are suggested. Some speculations are offered regarding the history of the crevasse on the basis of the complex icings found within it.

JOHN C. COOK (Southwest Research Center, San Antonio, Texas) *An Electrical Crevasse Detector.* Numerous fatal encounters with large crevasses concealed by bridges of drifted snow have occurred on the Greenland icecap and elsewhere. In response to an urgent need for rapid and reliable means of crevasse detection, a promising geophysical method has now been developed for the Department of Defense. This method is analogous to the four-electrode method of measuring earth resistivities. It differs in that an alternating dielectric displacement-current field is employed rather than a field of conduction current, since ice is essentially a non-conductor. The systems so far tested in Greenland and Antarctica, which employ this method, continuously indicate or record the capacitive transfer reactance between pairs of electrode sleds or vehicles. Systems have been successfully operated at surface speeds up to 20 mi/hr. Pronounced and distinctive electrical anomalies have been obtained at every crevasse tested to date. Typical crevasse-detector recordings and details of the equipment used are shown.

TOWNSEND CROMWELL (Inter-American Tropical Tuna Commission, Scripps Institution of Oceanography, La Jolla, Calif.) *Pycnoclines Created by Vertical Mixing.* Tank experiments are described in which pycnoclines are created by vertical mixing in water that is originally of uniform vertical density gradient. A qualitative explanation for this phenomenon is given. Data are presented which substantiate the prevalent idea that vertical mixing creates thermoclines in the ocean.

PAUL E. DAMON, LEON E. LONG, AND DONALD R. CARR (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Excess Helium and Argon in Minerals.* Helium in excess of that produced by the decay of uranium and thorium has been observed in several rocks and minerals. Since for *K-A* and *He* age determination absence of original inert gas must be assumed, it is necessary to understand the phenomenon producing the excess gas in certain cases. Excess argon as well as helium have been reported for beryl by Aldrich and Nier, but the argon excess included a considerable A^{36} content. New experiments reported here confirm the excess of A^{40} as well as He^4 in beryl but without detectable A^{36} or neon. The results show that the gas has been occluded by the mineral rather than being the result of radioactive or nuclear processes within the mineral. Further, it is

seen that beryl provides a method for sampling lithospheric gases and will yield information on the problem of the outgassing of the Earth.

A. L. Danis (University of Florida, Gainesville, Fla.) *The Growing Problem of Air Pollution in Florida.* This is a discussion of the start and growth of the air-pollution problem in Florida: weather associated with the fumigation of plants and citrus; its effect on health and animals; methods of measurement of the pollutants —hydrogen fluoride and sulphur dioxide; what is being done in Florida to counteract this problem.

B. Davidson, J. Halitsky, and I. Karmin (New York University, University Heights, New York, N. Y.) *A Micrometeorological Survey of the Hudson River Valley Near Buchanan, N. Y.* New York University is currently engaged in making a micrometeorological survey of the Buchanan, N. Y., area for the Consolidated Edison Co. of New York in connection with a power-generating station the company plans to erect at Indian Point Park. The objectives of the survey, the meteorological tower at the site, the instrumentation and general experimental procedures will be discussed briefly. An analysis of preliminary data obtained thus far will be presented to illustrate the marked diurnal variation of wind velocity in the valley.

Maurice J. Davidson and Edward Titus Miller (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *An Airborne Magnetic Survey of the West Indies, Gulf of Mexico, and the Eastern United States Continental Margin.* A reconnaissance airborne magnetic survey made during the summer of 1955 resulted in 25,000 miles of track; approximately 5000 miles over eastern United States continental margin, 6000 miles over Gulf of Mexico and Gulf Coast region, and 14,000 miles over West Indies Island Arc including 3500 miles in the vicinity of the Puerto Rico Trough.

General magnetic characteristics of surveyed areas: East Coast Continental Margins, 200–400 gamma anomalies near continental slope; Gulf Coast Margin, smooth over shelf, 100–200 gamma anomaly 60 miles inland, trending NNE; Puerto Rico Trough, smooth, no reflection of topography, particularly northern edge; Cayman Trench, Bartlett Deep, topography reflected, 100–200 gamma anomalies, 5–8 miles wide; Aves Swell, 100 gamma anomalies, 2–6 miles wide; Granada Trough, smooth; West Indies Island Arc, 50–100 gamma anomalies, 1–3 miles wide; Barbados Ridge, smooth, no reflection of topography; Curacao to Trinidad, many broad anomalies.

William E. Davies (Military Geology Branch, U. S. Geological Survey, Washington 25, D. C.) *Antarctic Stratigraphy and Structure.* Antarctica is divisible geographically and geologically into two distinct regions. West Antarctica, that portion lying south of the Americas, consists of folded ranges and plateaus with sediments deposited in Mesozoic and Tertiary geosynclines. These sediments along with the intrusives that invade them are of the Andean type and are traceable from Antarctica through the subantarctic islands of the Scotia arc to South America. East Antarctica, lying south of Australia and Africa, is a continental shield. In this area is a Precambrian basement of schists, gneisses, and intrusives overlain by a thick series of Paleozoic and Mesozoic sediments. The sediments are horizontal, and are thickest along the south and west sides of the Ross Sea. They have been intruded by numerous sills and dikes. Along the Antarctic Coasts south of Australia and the Indian Ocean the basement rocks form most of the ice-free areas with the sediments apparently confined to the higher plateaus in the interior of the Continent.

Along Palmer Peninsula in West Antarctica is a cordillera belt of multiple chains of folds which fan out into widely spaced arcs in the continental mass to the south. The shield in East Antarctica is bound by a series of horst blocks along the Ross Sea and the Ross Ice Shelf. Inland from the horst in a high ice-covered plateau with the sediments gently dipping away from the horst. Tertiary and recent volcanoes of the 'Atlantic type' lie along the edge of the Antarctic shield while those of the 'circum-Pacific type' was developed along the outer folds on the Palmer Peninsula in West Antarctica.

Wayne L. Decker (University of Missouri, Columbia, Mo.) *Estimation of Soil Temperatures from Meteorological Conditions.* The importance of soil temperatures is outlined, and the value of a system for estimation is discussed. The analysis which is described shows the relationship between soil temperatures and air temperature, solar energy, night cloudiness, wind velocity, and soil moisture. The correlation analysis estimates the multiple effect of these variables. Diagrams are presented showing the relationship between the estimated and measured soil temperatures.

Woodrow W. Dickey (U. S. Weather Bureau, Denver, Colo.) *The Use of Strictly Defined Terms in Summertime Forecasts.* The desirability of using a fixed set of strictly defined terms to describe the areal distribution of summertime showers and thunderstorms in the daily state forecast is discussed, and the feasibility of doing so is investigated. The areal distribution of afternoon and evening showers in Colorado and the variations of the distributions between various sections of the state are determined. The relative frequency of occurrence of forecast categories are determined for two sets of arbitrarily defined forecast terms. Significant differences are found, on the average, in the number of showers when various forecasting terms were used to describe their occurrence. From the results of the study certain recommendations are made which apply not only to the forecasts for the State of Colorado, but should be applied to all state forecasts of summertime shower activity.

C. Hewitt Dix (California Institute of Technology, Pasadena, Calif.) *Part of the Mechanism of Horizontal Shear Faulting.* Field studies of a fault suggest the following picture of a faulting process: (1) After any fracture of size comparable with the ultimate dimensions of the fault has first been established, resistance to further shear strain is less in the interior of the fault surface than it is at the boundary (below surface); (2) it is not uniform and may have a maximum at an interior point; (3) at such a maximum there is a tendency for local locking while slip takes place in the neighborhood on the fault surface; (4) this locking yields a local twist or rotation which increases the lateral stress, increasing the already locally maximal frictional resistance, making the lock more secure; (5) the localized lateral compressive stress is partially relieved by a local uplift; (6) adjacent to the locked region, minimal fault face pressures are generated which may result in local sagging; (7) and a series of alternating maxima and minima of resistance to shear,

of hills and depressions is thus generated. Some earthquakes are generated by yield of locally locked regions on faults. Both in time and in space the process is like that occurring in a relaxation oscillator.

WILLIAM L. DONN (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *On the Prediction of Storm Tides Generated by 'Northeast Storms'.* Astronomic tide has been removed from the storm tides of five strong cyclonic storms giving east to northeast winds along the east coast. On the basis of these few storms it is shown that a definite and possibly usable relation exists between observed wind and storm tide at a coastal station. The relation between storm tide and stage of astronomic tide is very important in forecasting potential tide danger. The wind velocity is of greater significance than the duration, indicating that the water transport involved in the tide is a local effect.

WILLIAM L. DONN AND MAURICE EWING (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Storm Surges and Edge Waves in Lake Michigan.* A storm surge (July 6, 1954) consisting of a long train of long-period waves (60–120 minutes) arrived at a number of stations on southwestern Lake Michigan simultaneous with an atmospheric pressure jump that traveled from north to south at 50 mph across the Lake. Ludington, about midway up the eastern shore of the Lake received the storm surge about seven to ten hours after the passage of the pressure jump. The high waves arriving simultaneous with the pressure jump can be explained on the basis of resonant coupling between the pressure jump and resulting 'edge waves' in the Lake. Observed period agrees closely with the theoretical edge-wave period. The high, post-pressure-jump waves at Ludington are explained as reflected, coupled edge-waves. Other observations are accounted for by means of phase and group-velocity relations.

WILLIAM L. DONN, PATRICIA MILIC, AND RENÉE M. BRILLIANT (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Gravity Waves and the Tropical Sea Breeze.* A microbarovariograph was maintained at Guantanamo Bay, Cuba, during the summer of 1952. Two groups of atmospheric pressure oscillations were recorded: a short-period group with period up to five minutes and a long-period group from about 15 to 40 minutes. The short-period oscillations commence with the onset of the sea breeze and persist for about three or four hours. With the firm establishment of the sea breeze, as shown by the temperature break, the short-period oscillations are replaced abruptly by those of the long-period group. The short-period pressure oscillations are explained as turbulence in the sea-breeze frontal zone. Those of long period are shown to be possible as pressure perturbations from propagating gravity waves traveling with the speed of the sea breeze, on the sea breeze interface, aloft. A more detailed model of the sea breeze is constructed from the observations and conclusions given.

MILTON DRAGINIS (University of Chicago, Chicago, Ill.) *New Measurements of Liquid Water in Convective Clouds.* Using a liquid water-content meter which involves the measurement of changes of conductivity of a paper tape with changes of wetness, observations have been made in a large number of cumulus clouds. One series of measurements was made in tropical cumuli, and another was made in clouds over the central United States. Examples of the variability of liquid water in convective clouds and typical values will be given. It is shown that the development of precipitation depends on the values of liquid water content. Comparisons of the observed values of liquid water with theoretical values based on an assumption of moist adiabatic lifting with no mixing lead to the conclusion that in clouds with precipitation there are regions with quantities of liquid water exceeding the theoretically calculated amounts.

HUGH L. DRYDEN (National Advisory Committee for Aeronautics, Washington 25, D. C.) *Comparison of 1906 Potsdam and 1936 National Bureau of Standards Absolute Determination of Gravity.* When P. R. Heyl and G. S. Cook made an absolute determination of gravity at the National Bureau of Standards in 1936, the value obtained was 20 milligals lower than that inferred from the classical 1906 Potsdam determination by F. Kühnen and Ph. Furtwängler. The author as an editorial reviewer of the Heyl and Cook paper reexamined the Potsdam determination, publishing the results as Research Paper 1502 of the National Bureau of Standards, now out of print. It was concluded that the Potsdam measurements better supported a value 12 milligals lower than that reported. The essential features of the suggested revision of the Potsdam result are reviewed.

PETER S. EAGLESON (Massachusetts Institute of Technology, Cambridge, Mass.) *Properties of Shoaling Waves by Theory and Experiment.* Experimental results on the transformation of wave height, length and steepness on a plane beach of 1:15 slope are compared with the small-amplitude theory of Airy. The effects of wave shape and beach slope on the applicability of the theory are shown through comparison with these data and with those of former investigators. The theory is found applicable to the prediction of steepness. Additional observations on the transformation of crest height and length are presented and discussed with respect to their influence on the mass transport velocities.

WALTER R. ECKELMANN AND DONALD S. MILLER (Lamont Geological Observatory Columbia University, Palisades, N. Y.) *New Uranium-Lead Age Determinations.* New specimens of uranium minerals from a number of localities have been subjected to chemical and isotopic analyses in an effort to further define the time of geologic formation. The Sunshine Mine, Idaho, contains pitchblende which cuts the St. Regis quartzite (Belt series) at the north limb of the Big Creek anticline. This pitchblende is at least 1.2 b y old, which is a minimum age for the deposition of the Belt series previously thought to be late Precambrian. Other ancient rocks that are relatively unmetamorphosed and that were previously thought to be more recent are the Lake Athabasca series (> 1.9 b y) and in the Witwatersrand area (≥ 2.0 b y). The Baden, Germany, deposit appears to be about 100 m y old. Other areas which will be discussed in terms of the new measurements are Crocker's Well and Nicoll's Nob, Australia; Prizbram, Czechoslovakia; Spruce Pine, N. C.; Middletown, Conn.; and the Huron Claim, southeastern Manitoba.

CARL R. EKLUND (U. S. Fish and Wildlife Service, Atlanta, Ga.) *Antarctic Fauna and Some of Its Problems.* Distribution of birds, mammals, fishes, and other forms of animal life common to the Antarctic region are discussed briefly. These include the emperor and

Adelie penguins, and the south polar skua, which species are considered indigenous to the area. Other bird species which either nest or spend considerable time in the region are mentioned. The four pinnepedia, considered endemic to the Antarctic zone are the Ross, crabeater, Weddell, and leopard seals, and their habits are cited. Occurrence of marine invertebrates and fishes is shown by phyla, class, or order. Terrestrial fauna consists primarily of arthropods. References are made to some of the past zoological studies, and the inadequacies of our present knowledge of Antarctic animals are considered. A zoological program which might be coordinated with geophysical studies is suggested. This includes collecting, bird banding, seal marking, life-history habits, population dynamics, food habits, seasonal movements, physiological studies, and location of the breeding grounds of the Ross and crabeater seals. The value of paleontological studies is discussed.

WALTER M. ELSASSER (University of Utah, Salt Lake City, Utah) *Convection in the Core.* Recently, Urey has thrown doubt on the possibility of maintaining thermal convection in the core by radioactive means. In view of the importance of this problem for geomagnetism, we have investigated possible alternatives and find the following fairly satisfactory: The inner core grows slowly by crystallization of iron, the rate being determined by the rate of loss of heat of the core toward the mantle. Convection is not mainly thermal, however, but is activated by direct changes of density of the fluid at the boundary of the inner core. These changes are attributed to relatively lighter solutes (oxides, silicates) assumed to exist in the liquid core in concentrations of a few per cent, but which do not precipitate as the iron solidifies. All quantities involved in the process can be bracketed within reasonably well-defined limits. Of course, it is not possible to decide at present between this and other models; we merely intend to demonstrate that the absence of radioactivity need not be fatal to a theoretical explanation of convection in the core.

ARTHUR ENGELMAN AND LAWRENCE COLIN (Griffiss Air Force Base, Rome, N. Y.) *Meteorological Effects on Propagation.* Preliminary results of an exhaustive index of refraction survey for the Rome, New York, area is presented. A sample consisting of radiosonde data for a one-year period has been analyzed and the results are presented in the form of average and 95 pct confidence limit curves. These averages are taken with respect to season, time of day, and air mass. Ray tracings and radar range and elevation angle errors appropriate to each average and three standard deviation curves are presented. Finally tentative plans for the complete study program will be detailed with special emphasis on a controlled experimental program to analyze the derived results. The use of these tropospheric average curves in the solution of the radio refraction problem will be outlined.

MARIANO A. ESTOQUE (University of Chicago, Chicago, Ill.) *A Prediction Model for Graphical Integration.* A simple two-level model for predicting the 1000- and 500-mb charts is described. The prediction equations can be integrated rapidly with the aid of graphical operations so that the method is suitable for routine use in ordinary forecasting offices. The results of 24-hour forecasts using the model are discussed.

H. P. EUGSTER (Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.) *Synthesis and Phase Relations of the Biotites.* Ferrous biotite, $KFe_3AlSi_3O_{10}(OH)_2$, an end member (Winchell's annite) of the biotites, has been synthesized hydrothermally. It is stable only at low partial pressures of oxygen. The upper stability limit of annite is given by a curve passing through the points 827°C and 2000 bars water vapor pressure, 785°C and 1000 bars, 762°C and 670 bars, 725°C and 330 bars. This curve lies 265°C lower than that for phlogopite. The breakdown products are sanidine + magnetite + vapor. In the presence of quartz, annite breaks down at 670°C and 1000 bars. The products of this reaction are sanidine + fayalite + quartz + vapor. Intermediate biotites, which lie on the join phlogopite-annite, have also been synthesized and their stability limits have been determined. The breakdown temperatures depend strongly on the Mg/Fe ratio. Biotites from extrusive and mafic intrusive rocks show a distinctly larger Mg/Fe ratio than most biotites from syenites, granites, and pegmatites. One of the factors responsible for this relationship may be the pronounced lowering of the stability limits of biotite with increasing Fe content. The upper stability limit of biotite represents the lower limit for the existence of the corresponding K-feldspar-pyroxene assemblages of the pyroxenehornfels and the granulite facies.

MAURICE EWING (Lamont Geological Observatory, Palisades, New York) *Some Problems of Antarctic Submarine Geology.* The available information about submarine geology in the Antarctic region is briefly surveyed. Suggestions for observations to be made during the International Geophysical Year are offered, particularly in relation to Pleistocene climactic changes.

MAURICE EWING AND BRUCE HEEZEN (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Mid-Atlantic Ridge Seismic Belt.* The Atlantic belt of earthquake epicenters follows the crest of the Mid-Atlantic Ridge and its prolongations into the Arctic and Indian Oceans with a precision which becomes more apparent with the improvement of our knowledge of the topography and of epicenter locations. These are all shallow shocks. Their apparent departure from the narrow crest of the ridge seldom exceeds the probable error of location. The crest is 30 to 60 miles wide, very rough, and on a typical section shows several peaks at depths of about 800 to 1100 fathoms. There is usually also a conspicuous median depression reaching depths of about 2300 fathoms. This is interpreted as an active oceanic rift zone which continues through the African rift valleys.

MAURICE EWING (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) AND FRANK PRESS (Seismological Laboratory, California Institute of Technology, Pasadena, Calif.) *The Long-Period Nature of S Waves.* It is generally observed that the periods of S are many-fold longer than those of P. The presence of strong short-period components in P, Lg, and T prove that the absence of these periods in S must be attributed to effects of transmission rather than to excitation. A mechanism of absorption of High Frequency S is suggested involving the presence of pockets of magma in the mantle. The paths along which High Frequency S propagates strongly, traverse regions which might be expected (on geological grounds) to be free of the magma pockets.

HAROLD W. FAIRBAIRN AND PATRICK M. HURLEY (Dept. of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge, Mass.) *Radiation Damage in Zircon from Eastern Massachusetts and Nova Scotia.* Radiation damage in zircon from 24 granites in eastern Massachusetts and mainland Nova Scotia has been investigated, using an x-ray diffractometer technique first described by the authors [1953] and later refined and made practical by Holland and Gottfried [1955]. Age ratios obtained are, with one exception, less than the ages obtained by the Pb-α(zircon) and Sr-Rb (biotite) methods, the discrepancy averaging about 35 pct. This may be caused in some cases by slow cooling of the granite after crystallization or perhaps by later regional metamorphism independent of the granite emplacement. In either case the zircon structure would be annealed in varying degree and yield a low age ratio. The ratio d_{200}/d_{112} can be used to distinguish eastern Massachusetts from Nova Scotia zircons, the characteristic range of values being well outside experimental error. If similar 'thumbprints' can be established in other areas these might provide an additional criterion for zircon in its role as provenance indicator.

RHODES W. FAIRBRIDGE (Dept. of Geology, Columbia University, New York, N. Y.) *Geotectonic Position of Antarctica.* The Antarctic Continent consists of two distinctive masses, three-quarters being a precambrian shield (East Antarctica) and one-quarter a region of mainly Paleozoic, Mesozoic, and Cenozoic fold belts (West Antarctica). They are separated by an asymmetric graben-like depression that extends from the Weddell Sea to the Ross Sea. The shield sector is extraordinarily similar in character to the other 'Gondwana' shields in Brazil, Africa, India, and Western Australia, while the folds of West Antarctica show genetic relations and structural continuity with those of the Scotia Arc and the South American Andes.

Geotectonically, Antarctica appears to be a 'normal' continent, containing all of the ancient, middling, and youthful elements characteristic of each of the other continents. Detailed exploration, although greatly hindered by the ice caps and adverse meteorologic conditions, may ultimately help to solve outstanding problems. In East Antarctica: Are there representatives of the early Mesozoic Cape Folds and unmetamorphosed Proterozoic? In West Antarctica: Are the main fold belts more similar to the eastern Australian ones or to New Zealand? Is the Ross-Weddell Graben potentially oil-bearing?

While the Wegenerian type of hypothesis is rejected by many geophysicists, Antarctica is paradoxically similar to other southern lands and plays a key role in any theories of large-scale continental displacements; it is obvious that more information is vitally needed, both of the continent itself and of the surrounding oceanic areas.

ROBERT G. FLEAGLE (University of Washington, Seattle, Wash.) *Comments on the Effect of Air-Sea Temperature Difference on Wave Generation.* Observations from certain ocean weather ships are used to determine whether or not observed wind speed in cold air (relative to sea temperature) leads to higher waves than does the same wind in warm air. The problem is to eliminate possible correlation between fetch and air-sea temperature difference. It is concluded that significantly higher waves are generated in cold air than in warm air, the difference amounting to roughly ten per cent of the warm-air values per degree centigrade.

ROBERT G. FLEAGLE (University of Washington, Seattle, Wash.) *On the Dynamics of the General Circulation.* The dominant features of large-scale atmospheric motion emerge from a relatively simple treatment of the hydrodynamic equations, thus providing clear, intuitive understanding of the relation between cause and effect in the general circulation. The analysis is made possible by applying the perturbation equations to a sloping stream surface located in the middle troposphere. For reasonable values of the arbitrary parameters, the results show that baroclinic disturbances are unstable poleward of a critical latitude, roughly 35°, and that the number of such unstable disturbances decreases from about ten at 45° to three at 70°. Greatest intensity occurs at about 60°. Jet streams must form close to the critical latitudes, and, in the case of long disturbances, at higher latitudes. Anticyclonic shear has a stabilizing influence, so that the normal velocity distribution in middle latitude offers considerable resistance to penetration of disturbances to low latitudes. Below the critical latitude unstable disturbances are possible only in relatively small areas where the hydrostatic stability is nearly zero. Growth of these disturbances is favored by anticyclonic shear, as well as by baroclinity and by high latitude. Disturbances of maximum rate of growth are practically non-dispersive so that their growth depends mostly on available potential energy; and, if sufficient energy is available, their identity can be maintained over extended time periods. Wave speed relative to the zonal current exhibits a maximum positive value at a high latitude.

JOHN C. FREEMAN, JR. AND LEDOLPH BAER (Gulf Consultants, Houston, Texas) *The Method of Wave Derivatives.* A convenient mode of expression of the equations of motion and continuity for a two-dimensional time-dependent fluid flow involves quantities (various combinations of the wave speed and velocity components) which move with the speed of the fluid plus the speed of waves or small perturbations. When the equations are expressed in this form, they suggest a method of computing the flow which uses graphic addition of isopleths and which gives some insight into the physics of the flow. This method of 'wave derivatives' is applied to the problem of following the motion and subsidence of an irregularly-shaped mound of water in a shallow, level-bottom sea. The motion displays a mixture of the properties of one-dimensional and axially-symmetric properties, in that a trough develops in the center of the elliptical mound.

JOHN C. FREEMAN, JR., AND LEDOLPH BAER (Gulf Consultants, Houston, Texas) *Graphical Computation of Hurricane Storm Tides.* The method of wave derivatives is applied to the non-linear perturbation equations for wind-driven two-dimensional time-dependent flow over a shoaling bottom. The space distribution of bottom contours can be much more detailed than the changes due to the storm. To avoid a needlessly fine grid and resulting short time steps, integrated values of wave speed were used to move the perturbations appearing in the equations of motion for one half-hour. The conditions prevailing during the Hurricane Baker of August 1950 which hit east of Mobile, Alabama, are used in an example. The computed and actual water levels at coastal stations are compared.

FRANCOIS N. FRENKIEL (Johns Hopkins University, Applied Physics Laboratory, Silver Spring, Md.) *Radioactive Pollution and Civil Defense.* Atmospheric pollution from radioactive wastes of nuclear reactors, experimental devices exploding at preassigned places, and bursts of nuclear bombs are considered. The discussion is limited to the meteorological aspects of these problems with particular attention to the possible predictions of pollution patterns. Two aspects of civil defense against fall-out are discussed. The first concerns the evaluation of possible civil defense measures under a threat of immediate nuclear attack; the second, the measures following the explosion. The operational use of high-speed computing techniques in the protection from atmospheric pollution by radioactive wastes is examined.

G. D. GARLAND (Dept. of Physics, University of Alberta, Edmonton, Canada) *Investigations of Gravity and Isostasy in the Southern Canadian Cordillera.* The results of gravity measurements and isostatic reductions for a region of western Canada extending from the interior plains to the Pacific Coast are presented. Departures from an Airy type of isostatic compensation are found to be small compared to those observed in some other young mountain ranges, but these appear to be correlated with the tectonic regions. Areas of the Coast Range intrusive rocks show negative anomalies, which allow the distribution of this material at depth to be suggested. By contrast, regions of maximum elevation in the true Rocky Mountains give positive isostatic anomalies, suggesting that the crust has not completely adjusted itself to the increased elevation formed by overthrusting in these areas. The position of the Rocky Mountain Trench in relation to the gravity field is discussed.

ROBERT E. GEBHARDT (U. S. Coast and Geodetic Survey, Corbin, Va.) *Progress Report on the Fredericksburg Magnetic Observatory.* An outline and description of the progress to date on the installation and activation of instrumental equipment and other facilities at the Fredericksburg Magnetic Observatory of the Coast and Goedetic Survey are presented.

JOHN GERGEN (University of Minnesota, Minneapolis, Minn.) *The Black Ball: A Simple Atmospheric Infrared Detector.* The problem of the atmospheric infrared heat balance has been solved graphically and analytically, but almost no experimental evidence exists to verify the calculations. The BB (Black Ball) is a device which can be flown on an ordinary radiosonde and indicates a temperature which is related to an equivalent radiation temperature, which in turn is a measure of the total incident infrared flux at any point. The observed radiation temperature excess over the air temperature at a point can be shown to be directly related to the radiative cooling of the atmosphere at the measured point. The observed Black Ball temperature excesses must be corrected roughly by a factor of two since convection processes prevent a black absorber from attaining true radiative equilibrium. These convection effects in the BB are minimized by the use of an infrared-transparent convection shield and can be compensated for by calculation. Approximately 250 BB flights have been made at Minnesota during the past year and an annual survey of the atmospheric radiation will be completed by the summer of 1956. Average radiation temperature soundings and some unusual individual soundings are presented.

R. L. G. GILBERT (Dominion Observatory, Ottawa, Canada) *Some Comments on the Results Obtained with the Cambridge Pendulum Apparatus in North America.* The results obtained by the Dominion Observatory with the Cambridge pendulum apparatus in 1952 and 1953, whilst establishing a gravity base line from Mexico City to Fairbanks, Alaska, are analyzed with a view to improving their consistency. The analysis shows one pendulum to be much more stable than the other four, and results obtained from this pendulum are quoted. These are compared with the results published by the Dominion Observatory, and with those obtained by the Woods Hole Oceanographic Institution using the Gulf pendulum apparatus. An investigation into the behavior of the pendulums at other times is attempted, and tentative conclusions drawn which should prove valuable in the planning of future pendulum gravity surveys.

BRUCE GILCHRIST (Institute for Advanced Study, Princeton, N. J.) *Error-Free Data for Numerical Weather Prediction.* The problems concerned with obtaining, transmitting, and processing meteorological data prior to their use in a forecasting system are discussed. The importance of transmitting only useful information is emphasized, as is the necessity of providing adequate checking facilities at all stages. The conclusions drawn are mainly based on the needs of numerical weather prediction, although it is shown that most of the conclusions hold generally.

BRUNO J. GILETTI AND J. LAURENCE KULP (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Application of Tritium Measurements to Oceanography and Meteorology.* Tritium (H^3), both natural and from thermonuclear processes, is used as a tracer in meteorologic and oceanographic water movements. Rains collected at Lamont Observatory show an average T:H value of 8×10^{-18} with a scatter of a factor of about 4. During thermonuclear test periods, this value has reached 1240×10^{-18}. Superimposed on this variation is that due to air-mass movement. In eight cases southerly warm air masses carried water vapor of higher tritium content than adjacent cold air masses. North Atlantic surface waters averaged 1.3×10^{-18} in 1953. In two samples taken in mid- and eastern Atlantic little increase following the H-tests in the spring of 1954 was observed. One sample close to the American coast was up by a factor of four. The tritium content down to 100 m depth decreases slightly, indicating an apparent age of three years. The tritium content of deep water at 2000 m in the western North Atlantic suggests a minimum age of 25 years. Methods, assumptions, and limitations will be discussed.

LOUIS M. GLYMPH, JR. (739 Northampton Dr., Silver Spring, Md.) *Importance of Sheet Erosion as a Source of Sediment.* The paper discusses briefly the methods of measuring sheet erosion, reviews procedures for applying results of plot studies in calculating sheet erosion rates on a watershed basis, and presents the results of sediment source studies on a number of watersheds throughout the country.

L. C. GOTTSCHALK (3805 Seventh St. S., Arlington, Va.) *Problems of Predicting Sediment Yields from Watersheds.* Outline of the needs for information on watershed erosion and sediment yields in planning and operations work. Problems associated with predicting sediment yields from watersheds. Purpose of the symposium is to present the latest research findings and the

present state of knowledge regarding erosion and transportation of sediment. The published results of the symposium will provide a valuable guide to technicians engaged in watershed work.

LAURENCE M. GOULD (Carleton College, Northfield, Minn.) *Highlights of Antarctic Exploration.* Antarctic exploration falls into phases or loosely defined periods. The first was the demonstration by James Cook, from 1772 to 1775, that if any possible land mass or terra australis existed, it was much smaller than earlier guesses had supposed. In the early 1820's British and American sealers and the Russian admiral Bellinghausen made further penetrations, chiefly in the Atlantic sector. From 1838 to 1842 the areas chiefly below Australia were explored by Durville, Ross, and Wilkes. The latter, however, further circumnavigated the whole area and demonstrated the existence of a continental land mass for the first time.

The next onslaught came at the turn of the century, from 1898 to 1904, through the achievements of Gerlache, Scott, Bruce, Drygalski, and Nordenskiold. Then came one of the greatest ages of all—Shackleton, Scott, Amundsen, and Mawson, lasting roughly from 1907 through 1913. Finally, the modern age was ushered in, beginning in the late 1920's and early 1930's. Most of the names associated with this phase, which brings us right into the present, are familiar to you. Amongst the the outstanding are Byrd, Wilkins, Mawson, Riiser-Larsen, Rymill, Ellsworth, Ronne, and the notable Norwegian-British-Swedish Antarctic Expedition of 1949–1952.

M. L. GREENOUGH (National Bureau of Standards, Washington 25, D. C.) AND JULIUS F. BOSEN (U. S. Weather Bureau, Washington 25, D. C.) *FOSDIC—A New Approach to Storage and Utilization of Digital Records.* Under Joint Meteorological Committee sponsorship, the National Bureau of Standards has developed a new Film Optical Sensing Device (FOSDIC PC-1), designed for high-speed digital reading by electronic scanning of the microfilm of punched cards. FOSDIC makes it possible for the National Weather Records Center to test the usefulness of punched card microfilm as the basic medium for storage of digital machine records in the WBAN data library. This use of microfilm retains excellent compatibility with conventional and prospective automatic data processing equipment and techniques, and promises to provide a much improved weather data library and processing service at lower costs than are now possible. It offers, further, a solution to the pressing problem of space and storage for an ever-growing mountain of punched cards in the WBAN library.

ROSS GUNN (U. S. Weather Bureau, Washington 25, D. C.) *The Hyperelectrification of Raindrops by Atmospheric-Electric Fields and the Observed Space-Charge Densities Inside an Active Thunderstorm.* The role of atmospheric-electric fields in selectively charging raindrops is analyzed and compared with direct measurements made inside an active thunderstorm. Expressions are developed for the free charge transferred to conducting spheres polarized by an electric field and immersed in an environment in which the positive and negative ionic conductivities are different. Measurements in a wind tunnel operating with ionized air confirm the analysis.

Because the electrical conductivities inside a cloud and in the clear air immediately outside are so very different, electric fields acting across such a cloud boundary selectively concentrate ions of a single sign in a space-charge layer. Extensive regions are thereby established wherein the positive and negative ionic conductivities are notably different. Cloud and raindrops in this transition layer become hyperelectrified. Expressions for the mean space charge in the transition layer are developed. The estimated drop charges and space-charge densities are found to agree with earlier measurements made at various levels inside an active thunderstorm. It is found that a large fraction of the free space charge inside a thundercloud is carried by the precipitation and is roughly proportional to the electric field intensity within the cloud boundary transition layer. Since transition cloud layers near the cloud boundaries play an important part in the electrification process, precipitating cumulus-type clouds developing in a clear air environment are most likely to produce active lightning.

WILLIAM H. HAGGARD AND HUGH S. WHITE (U. S. Weather Bureau, Washington 25, D. C.) *Some Aspects of Hurricane Climatology.* The increased attention devoted to hurricane statistics has renewed the requirement for an adequate climatology of tropical storms. The program within the Climatological Services Division of the U. S. Weather Bureau to improve and extend climatology of hurricanes and tropical storms is described. Several aspects of tropical storm climatology are discussed. Chief among these are the results of investigations for secular trends in storm frequencies, areas of occurrence, and vulnerability of coastal areas.

FERGUSON HALL (U. S. Weather Bureau, Washington 25, D. C.) *The Spectrum of Data Processing.* The spectrum of meteorological phenomena ranges from sluggish variations in the general circulation to transitory fluctuations lasting no more than a fraction of a second. Data requirements for describing meteorological events as well as the type of processing to be accorded the data vary over wide limits depending upon the portion of the meteorological spectrum involved. The nature and extent of communication of raw and processed data back and forth within a weather service also depend upon the scale of the phenomena, but in addition are affected by the functional organization of the weather service using the data, that is, the extent to which their activities harmonize with the different scales of weather activity. Some suggestions are offered for optimizing the processing of data in different portions of the meteorological spectrum.

E. T. HARDING (U. S. Navy, % FPO, Norfolk 11, Va.) *Weather Information and Forecasts in a Fleet Operation.* The role of meteorological information and forecasts in a Carrier Task Force operation will be discussed, with emphasis on how information should be presented so as to be of most value in planning and conducting the operation.

PAT. J. HARNEY (Air Force Cambridge Research Center, Cambridge, Mass.) *Aircraft Temperature Measurements with Vortex Thermometers.* The vortex air thermometer is rapidly becoming a standard for use on weather reconnaissance aircraft. Some interesting examples of measurements with the Naval Research Laboratory model on the Air Force Jet Stream Project show its value. Variations in the performance of different models or of the same design in different installations or under different conditions call for a better understanding by the user of the data taken. The

problem of a standard of reference and the effects of wet air remain with us.

D. Lee Harris (U. S. Weather Bureau, Washington 25, D. C.) *The Storm-Surge Problem in the United States.* The storm-surge problem as it exists on the Atlantic, Gulf, and great Lakes Coasts of the United States is reviewed. Hydrographs showing the variation of the water level in Lake Erie and along the coast lines during severe storm-surge conditions are shown. The problems in separating the astronomical tide from the meteorological tide are discussed. It is found that a complete separation is impossible but that a useful degree of separation can be obtained by defining the storm surge as the difference between the observed tide and the predicted by tide machines such as that used by the Coast and Geodetic Survey.

D. Lee Harris and Arthur Pore (U. S. Weather Bureau, Washington 25, D. C.) *Case Studies of Recent Storm Surges.* Hydrographs of the storm surge, defined as the difference between the observed sea level and that predicted by the U. S. Coast and Geodetic Survey tide machine, have been prepared for a number of recent storms, both tropical and extra-tropical. Hourly predictions of the tide, as well as hourly observations of the tide height, were used in these hydrographs. Hydrographs for Coast and Geodetic tide stations along the East Coast for several hurricanes and extra-tropical storms will be shown. It is found that the maximum surge height associated with hurricanes generally occurs as or slightly after the storm passes nearest the station. However, with extra-tropical storms, the maximum surge height occurs before the storm makes its nearest approach to the station. This implies that the depletion of pressure near the center of a hurricane is the dominant factor in producing the hurricane surge, and that the wind is the dominant factor in producing the storm surge by an extra-tropical storm.

Lloyd L. Harrold (1527 Denman Ave., Coshocton, Ohio) *Yield of Water from Small Agricultural Watersheds.* This paper presents methods of reporting runoff data from small agricultural watersheds of 29 to 17,540 acres near Coshocton, Ohio. From 18 years of field records of precipitation and runoff, a relationship was established to provide a means of estimating, from a 46-year precipitation record, 12-month runoff values for recurrence intervals of two to 100 years for this watershed size range. The actual 18-year field records of runoff were used to develop minimum runoff values for periods of one to 12 months. Seasonal occurrence of the four lowest values and the duration of minimum flow throughout the period of record were developed. Minimum five-day stream flow for months of June, July, and August for each year of record is shown. This paper does not attempt to present all the results of this study as the data would be too voluminous. Sufficient data are shown to reveal the methods used.

H. S. Heaps (Nova Scotia Technical College, Halifax, Nova Scotia, Canada) *The Effect of Elastic Intrusions upon a Gravitational Stress.* A theoretical investigation is made of the state of stress within an elastic material subject to the force of gravity and containing intrusions of different elastic properties. It is assumed that the elastic properties of the intrusions do not differ greatly from those of the surrounding medium. The formulas obtained are expressed in a form that is independent of the specific shape of the intrusions. Figures are included to show the effect of a single intrusion upon the shearing stress at points within the surrounding material.

Roy W. Hendrick (Cornell Aeronautical Laboratory, Buffalo, N. Y.) *Corona Point Discharge and Re-Evaluation of Thundercloud Electric Fields.* The essential parameters determining corona point discharge are the first powers of the voltage on the point and the speed with which the ions move away from the point. The latter is determined primarily by wind or by ambient field depending on the geometry and the conditions. The discussion in essence is an extension of earlier preliminary reports by R. W. Hendrick, Jr., and the author published in the December, 1955, issue of the Bulletin of the American Meteorological Society on corona discharge radiosonde investigations of thundercloud fields.

J. P. Heppner (Naval Research Laboratory, Washington 25, D. C.) *Forthcoming Geomagnetic Studies from Rocket Vehicles.* Electric currents producing magnetic disturbances will be investigated by accurate magnetic measurements from rocket vehicles. Magnetometers carried by Aerobee-Hi rockets at Fort Churchill, Canada, during IGY will be used to study auroral-zone currents. Measurements from Earth satellite vehicles to determine the existence or non-existence of extra-terrestrial ring currents are seriously being considered. The extreme accuracy required for definitive data from these measurements can be obtained from the proton precessional magnetometer developed for rocket use by Varian Associates. With this instrument it should also be possible to study the relatively weak currents producing quiet-day diurnal variations. During IGY attempts will also be made to locate ionospheric irregularities and the source of rapid pulsations by means of miniature component magnetometers sensitive only to rapidly varying fields.

John Hershberger (U. S. Coast and Geodetic Survey, Washington 25, D. C.) *A Comparison of Earthquake Accelerations with Intensity Ratings.* The maximum accelerations recorded on 108 strong-motion records obtained in 60 earthquakes were compared with the intensity ratings assigned to the places where the records had been obtained. The results seem to show that acceleration alone cannot be used as a measure of intensity.

L. F. Herzog, W. H. Pinson, Jr., and R. F. Cormier (Department of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge, Mass.) *Sediment Age Determination by Rb-Sr Analysis of Glauconite.* This paper reports initial efforts to determine the absolute age of sedimentary rocks accurately dated by index fossils by the analysis of glauconite in such rocks for Rb and radiogenic Sr content. A mass spectrometric isotope dilution method was used. As analyzed, the four samples contain 200–300 ppm, Rb by weight, from 0.06 to 0.42 ppm radiogenic ^{87}Sr, and from 8 to 30 ppm total Sr. Part of the ordinary Sr is believed to be contamination from admixed $CaCO_3$ impurity. Three samples are from the Upper Cambrian or lowermost Ordovician of North America and Europe; the fourth sample is from the well-known Upper Cretaceous New Jersey greensands. The range of daughter/parent nuclide ratios for the three older samples is 420 to 500×10^{-6}, giving a range of ages between 300 and 360×10^6 years if the half life of ^{87}Rb is assumed to be 50×10^{-9} years. The Cretaceous sample has a d/p ratio of 79×10^{-6} and an age of

$54 \pm 30 \times 10^8$ years. The large uncertainty in the age of this sample is a result of its small radiogenic 87 enrichment; a separate isotopic analysis of this Sr should reduce this uncertainty to less than ± 15 pct. The accuracy of the other three analyses is already better than this, but can also be increased by separate isotopic analysis of sample Sr. The ages found are reasonable. The North American Cambrian samples are identical in Rb and radiogenic Sr content, as well as age, although from localities over 1000 miles apart, indicating that they probably have not lost or gained appreciable Rb or Sr since they formed. The method shows great promise for dating post-Precambrian sedimentary rocks. Additional analyses are in progress.

VICTOR F. HESS AND A. W. MANNING (Fordham University, New York, N. Y.) *A Study of the Ionization Produced in Various Gases by Cosmic Radiation.* To study the ionization produced in various gases by cosmic radiation, four geometrically similar brass chambers differing greatly in size were used with the Gish-Sherman ionization apparatus. Each of the chambers filled with the gas being studied was placed in an iron house with walls ten cm thick. The chambers were slowly evacuated in steps and the ionization measured at various pressures. As expected, the relationship between the ionization measured and the pressure remained linear to a very low pressure. The residual ionization was determined by using the method of Hess. By plotting the ionization of each chamber at 76 cm Hg pressure as ordinate and the ratio of the area to the volume of each chamber as abscissa, and extrapolating for infinite volume, the amount of cosmic radiation without any secondary radiation from the walls was obtained. Experiments seem to indicate that a linear relationship exists between the ionization and the molecular weight of gases of low molecular weight.

E. WENDELL HEWSON (University of Michigan, Ann Arbor, Mich.) *Atmospheric Pollution by Aeroallergens.* There has been considerable activity in recent years in studying industrial pollution, but pollution by aeroallergens has been relatively neglected. Air-borne pollen, spores, rusts, and smuts are a definite health hazard to millions of persons who suffer from allergic reactions to these particles. The several types of aeroallergens are described briefly, and the seasonal and areal occurrence of the most important ones outlined. The various influences of meteorological factors such as turbulence, stability, temperature, humidity, and precipitation on pollen production, potency, emission, take-off, transport diffusion, deposition, and refloatation are discussed. The problems involved in obtaining accurate concentration measurements are outlined. Substantial benefits may be expected if accurate forecasts and adequate control measures can be developed. The presentation concludes with a description and preliminary results of the project sponsored by the National Institutes of Health in which specialists in meteorology, medicine, public health, botany, and ecology are attacking the problem on a broad front with the cooperation of prisoners and administration at the State Prison of southern Michigan at Jackson.

H. W. HISER (University of Miami, Coral Gables, Fla.) *Gulf Stream Effects on Squall Lines as Observed on Radar at Miami.* Radar photographs are presented which show marked development of squall lines moving from land to sea on the east coast of Florida. In some cases, very severe turbulence was reported in the squall lines when they were over the Gulf Stream while only light turbulence and a small amount of precipitation occurred in the same squall lines over peninsular Florida before they moved out to sea. Synoptic weather analyses and water temperatures are included in the squall-line studies.

J. E. HOGG (Dept. of Physics, University of Toronto, Toronto, Canada) *The Determination of Uranium Mineral Ages by the Lead 210 Method.* A modification of the lead 210 method of age determination of Houtermans and Kulp has been developed, and new ages produced. A proportional counter has been constructed into which the lead samples are introduced as lead tetramethyl vapor, which allows the beta activity of the lead 210 to be measured directly and analyses to be made on extremely small samples. Causes of the discrepancies among ages resulting from the various methods are discussed.

J. B. HOLLEYMAN AND ROY H. BLACKMER, JR. (Illinois State Water Survey, Urbana, Ill.) *A Meso-Analysis of a Well-Defined Cold Front on September 21, 1947.* A meso-analysis is made using data from the Thunderstorm Project in Ohio during 1947. The spacing between stations in the Ohio network was two miles. The network was approximately ten miles wide by 20 miles long. The case selected for analysis is that of a well-defined cold front which had earlier moved into the circulation of a dissipating hurricane and on the evening of September 21 crossed the network. Five-minute maps for the period 19h 25m–20h 30m are analyzed for pressure, wind, temperature, moisture, and precipitation. In addition, upper-air soundings are used to show the relation of events in the free atmosphere to those on the surface. The surface maps are combined into composite maps to illustrate interrelation of the different parameters. Features that stand out in this analysis are the pressure jump line immediately ahead of the cold front, the meso-lows that develop just to the rear of the pressure jump line, the small-scale undulations that exist along the pressure, temperature, and moisture discontinuities, and the extremely sharp gradients that exist in these parameters. This work was supported by the Signal Corps Engineering Laboratories.

J. LEITH HOLLOWAY, JR. (U. S. Weather Bureau, Washington 25, D. C.) *Smoothing, Filtering, and Inverse Smoothing of Time Series.* A theoretical analysis is made of the modification of meteorological time series effected by various smoothing methods. Several smoothing methods used in meteorology are analyzed to determine whether their designs are optimum in respect to the purposes for which they are intended. Smoothing is shown to be a special type of filtering. The reversibility of smoothing and filtering processes is discussed, and several techniques for performing inverse smoothing are described.

W. T. HOLSER (University of California, Los Angeles 24, Calif.) AND C. J. SCHNEER (University of New Hampshire, Durham, N. H.) *Polymorphism in the Earth's Mantle (Seismic discontinuities without chemical change).* The authors briefly review the seismic considerations of their paper on geochemistry (see full abstract in Section of Tectonophysics, paper 2).

W. T. HOLSER AND C. J. SCHNEER (University of California, Los Angeles 24, Calif., and University of New Hampshire, Durham, N. H.) *Polymorphism in the Earth's Mantle.* Polymorphism has been proposed to explain seismic discontinuities without chemical

change. Topological and thermodynamic classifications of polymorphism indicate a much wider range of possible types than previously described, with the further possibility of seismic discontinuities independent of density changes. Polymorphic transformations are topologically classified as: (1) open packing to cp (closest-packed), (2) rearrangements of interstitial atoms in cp structures, (3) coordination change, (4) electronic transformation, and (5) rearrangement of cp atoms. Calculation of repulsion energy for coordination change indicates an increase of cation coordination number with high pressure, but the effect of temperature cannot be generalized. Transformations of types (1), (3), and (4) are first order, with a volume change, latent heat, and change of elastic constants. Types (2) and (5) are second order in an ideal case, with abrupt change of elastic constants at a critical point, but with volume and heat changes spread over a wide range. With increasing depth a single compound may undergo a series of transformations with consequent effect on the seismic observations: a low-pressure open structure collapses to cp, the cations move from tetrahedral to octahedral holes, then into high coordination positions where they are an essential part of the packing; and ions release their electrons to the conducting state (starting with the oxygen ion). While interstitial atoms are still present, they may rearrange in response to temperature or pressure changes. At some undetermined stage cp atoms may rearrange, as from cubic cp to hexagonal cp.

D. W. Hood (Department of Oceanography, Texas A and M College, College Station, Texas), Elizabeth Rona, and L. K. Akers (Oak Ridge Institute of Nuclear Studies, Oak Ridge, Tenn.) *Determination of Manganese in Sea Water:* A joint project of ORINS and Texas A and M was undertaken to determine the concentration of various elements in sea water by activation analysis. This paper deals with the determinations of manganese. The origin of manganese of the unusually high concentration in some ocean-bottom sediments (red clay) and that of the manganese nodules is still unexplained. An attempt was made to determine how much of this manganese was contributed by sea water. Separation from other elements was tried by: (1) liquid-liquid extraction with chelating agents; and (2) by coprecipitation. The data available with (1) indicate that Mn is present in sea water in a non-extractable form. This was substantiated by the results of (2). The concentration of manganese was determined by activation analysis. The gamma radiation was measured in a scintillation spectrometer and this measurement was compared with that of a sample of known manganese content.

Robert A. Hoover (U. S. Weather Bureau, Washington 25, D. C.) *The Characteristics of Hurricanes Associated with Rapid Rises in Sea Level.* The almost forgotten concept that hurricanes contain distinct convergence, or wind shift, lines is revived and used to account for the formation of the hurricane surge. Hurricane tracks are presented to show that severe surges are produced when the hurricanes have a linear path of considerable length normal to the coastline of entry.

John G. Housley and Donald C. Taylor (Hydrodynamics Laboratory, Massachusetts Institute of Technology, Cambridge, Mass.) *Application of the Solitary-Wave Theory of Shoaling Oscillatory Waves.* The celerities of shallow water waves were studied as a function of wave height and wave length or period. The experimental celerities were compared to the theoretical values obtained from the oscillatory (Stokian) wave theory and the solitary-wave theory. (The cnoidal wave theory was found to be experimentally valid for the transition but is practically inapplicable for prediction.) On the basis of this comparison, an effective wave length could be defined below which the Stokian theory applies, and above which the solitary-wave theory gives better results.

Lester F. Hubert (U. S. Weather Bureau, Washington 25, D. C.) *Rocket Observations in Meteorology.* Material presented here is largely due to the analysis of the Aerobee Rocket photographs made from 100 miles over White Sands, N. Mex., fired by Naval Research Laboratory, October 5, 1954. Rockets are capable of furnishing valuable measurements of radiation and vertical distribution of ozone—the latter has a significant 'synoptic' variability which is largely unknown. Aside from radiation-type measurements which require difficult instrumentation, ordinary photography is valuable, even though limited to visible phenomena. Perhaps greatest use is on a selective basis, especially in the tropics. Several specific problems amenable to photographic investigation are described. On a routine basis, a use is suggested in connection with water-vapor transporting vortices that are sufficiently small to be missed by the ordinary upper-air network, and slides are shown to illustrate this point. A composite photograph of the tropical storm photographed from the rocket on October 5, 1954 is also shown. Finally, one of the movies taken on this rocket flight will be shown.

Richard C. Hubley (National Academy of Sciences, Washington 25, D. C.) *Turbulent Transfer of Energy over an Isothermal, Melting Snow Surface.* In earlier investigations of energy transfer at a melting snow surface, both H. U. Sverdrup and C. C. Wallén made calculations of Austausch coefficients for a height of one cm above the snow surface using temperature, vapor pressure, rate of snow melt, and radiation-exchange data obtained from field observations. Expressions were then obtained for the Austausch coefficient at one cm above the surface as a linear function of wind speed. On the other hand, the scatter of individual values of the coefficients was sufficiently great in both cases that considerable doubt remained concerning the validity of expressing the Austausch coefficient close to the surface as a simple function of wind speed. A similar investigation of energy exchange over melting snow was made by the writer in 1953 and 1954 using more accurate instrumentation and observation methods than had been available to Sverdrup and Wallén. Coefficients calculated in the present study varied only slightly from a linear function of wind speed. Large individual deviations from a linear function of Austausch coefficients computed by Sverdrup and Wallén appear to be due to observational errors and inadequacy of methods used to estimate lapse rates of temperature and vapor pressure at one cm above the snow surface. Evidence is also found in the present study for the existence of a semi-laminar boundary layer of considerable thickness at low wind speeds with a first-order discontinuity in Austausch coefficient at the upper boundary of this layer.

F. A. Huff and J. C. Neill (Illinois State Water Survey, Urbana, Ill.) *Distribution of Point and Areal*

Rainfall Rates. Use of special recording raingages enabled recording of one-minute rainfall amounts from a 50-gage network on a 100-sq mi area in central Illinois during the 1952-1953 thunderstorm seasons. The one-minute amounts from 19 storms, tabulated in conjunction with a radar-rainfall measurement program, have been used to study the distribution of rainfall rates in shower-type storms under warm season conditions on both a point rainfall and areal mean rainfall basis. Within the 100-sq mi area, smaller areas of 10, 25, and 50 sq mi were studied to obtain an indication of the effect of changing area on the distribution of areal mean rates. The degree to which averaging suppresses details of high rates, as well as the general effects of the averaging process on the distribution curve, was also studied by comparing the distribution of point rates when the rates were based on 1-, 5-, 10-, 15-, and 30-minute averages. The same one-minute data were utilized to obtain a relation between point and areal mean rainfall rate for areas of 10, 25, 50, and 100 sq mi. Results of this study are compared with those from a similar study based on total storm rainfall.

EDWARD O. HULBURT (U. S. National Committee for IGY, Washington 25, D. C.) *Geomagnetic Disturbances.* The facts and theories of geomagnetic storms and the three great overhead currents of geomagnetic disturbance inferred from surface observations will be described. The experimental program of magnetic observations during the International Geophysical Year designed to determine the location and distribution of the inferred overhead currents will be explained.

PATRICK M. HURLEY AND WILLIAM H. PINSON, JR. (Massachusetts Institute of Technology, Cambridge, Mass.) *Variations in Radioactive Elements between Mafic Rock Provinces.* For mafic extrusive and intrusive rocks of probable sub-crustal origin the ratio potassium/equivalent uranium is approximately 5×10^{-5} as an average for a large number of samples from widely scattered areas. The relationship between potassium and equivalent uranium varies considerably between groups of mafic rocks from different areas of the continental and oceanic crust, but within any single petrographic province the relationship is much more constant regardless of variations in the absolute abundances. It is believed that this indicates a non-uniform upper mantle. Heat-flow considerations also require an upward fractionation of U with respect to K, so that a vertical rather than horizontal variation in the ratio of these components is visualized. In this case the differences between petrographic provinces would result from different source depths. Absolute abundances of radioactive elements between provinces vary by a factor of more than three (0.8 to 3 ppm equiv U) despite a lack of correlation with major components that would indicate different degrees of the rocks.

M. J. S. INNES (Dominion Observatory, Ottawa, Canada) *Gravity and Isostasy in Central Quebec.* A belt of intensely negative isostatic gravity anomalies has been partially outlined in northern Quebec as the result of a regional survey in 1954. The belt, which is nearly 140 miles wide and at least 400 miles long, trends northeast along the height of land and parallels the northern border of the Grenville geological province. The gravity minima, as much as -75 milligals on the Airy system, are believed related to large masses of granite emplaced during a period of late Precambrian mountain building. The retention of these large anomalies for great periods of geologic time is discussed in relation to isostasy and to the strength of the crust and the interior.

M. J. S. INNES AND A. M. BANCROFT (Dominion Observatory, Ottawa, Canada) *Recent Gravity Work of the Dominion Observatory, Ottawa, Canada.* A summary of the activities of the Dominion Observatory in recent years to establish a regional network of gravity stations throughout Canada is presented. Particular reference is made to the base looping program carried out in 1955 in which air transportation and three gravimeters were employed to establish 48 primary bases between Vancouver, B. C., and Gander, Newfoundland. Also given are the results of a series of measurements along a north-south line between the fundamental gravity stations in Ottawa and Washington. Problems relating to the calibration of the gravimeters employed and the adjustment of the results to a common datum are discussed.

J. A. JACOBS AND T. OBAYASHI (University of Toronto, Toronto, Canada) *The Sudden Commencements of Magnetic Storms.* A statistical investigation of the world-wide electric current systems corresponding to SC's has been carried out. The storm-time variation Dst and the disturbance diurnal variation Ds of SC's are derived separately from the results of the average local-time variations in the magnetic field at different latitudes. A conspicuous current system is found in the inner polar regions, and a concentrated current flow is also confirmed along the geomagnetic equator resembling the current system of an enhanced Sq-field. The inner polar region currents flow towards the meridian at about 9h local time and are supposed to complete their path along the outer auroral zone in opposite directions in the forenoon and afternoon hemispheres. It is of interest that the pattern of this atmospheric-electric current system is very similar to that caused by an electric doublet centered on the highly conducting region near the pole. Some observed facts concerning the statistical nature of SC's can be explained by these current systems.

W. S. JARDETZKY (Lamont Geological Observatory, Columbia University, Palisades, N. Y., and Manhattan College, New York, N. Y.) *Isostasy and Pole Shift.* Two contradicting conclusions about the direction of the pole shift were drawn by Milankovitch and Kuiper. The derivation is based in both cases on the simplest interpretation of conditions of isostasy and existence of the *Polflucht* force. It may be easily shown, however, that the Airy's hypothesis is a natural one for the sialic layer only. For a progressing solidification of the crust, the Hayford's modification of the Pratt's hypothesis can correspond to actual conditions, but a regional compensation as suggested by Vening Meinesz seems to yield a better approximation. However, neither of these conditions is strictly satisfied. The results based on insufficient theoretical approximations concerning the stratification in the Earth may be therefore inconclusive. A more close approach can be derived from the fact that the mass distribution in the Earth's crust is antisymmetric. It must be confirmed by geological data. It can be shown that this approach agrees with Milankovitch's conclusion. The North Pole seems to have changed its position because of the gliding of the crust. The direction of such a gliding is determined by southward displacement of Hawaii region.

C. Y. JOHNSON AND J. P. HEPPNER (Naval Research

Laboratory, Washington 25, D. C.) *Positive and Negative Ion Composition of the E-region from Rocket-Borne Mass Spectrometer Measurements.* Results of two Aerobee rocket flights at White Sands Proving Ground, New Mexico, are reported. The rockets were instrumented identically with two Bennett mass spectrometers per rocket for simultaneous measurements of positive and negative ions in the mass range 5 to 58 AMU. The spectrometers will operate above 93 km where the mean free path is long enough for resolution. In the NRL-23 flight, 01h 39m MST, July 8, 1955, positive ions appeared only at mass 28 between 93 km and the peak of flight at 115 km. There was no indication of negative ions on this night-time flight. In the NRL-24 flight, 10h 16m MST, November 29, 1955, negative ions appeared at mass numbers 46, 32, 29, 22, and 16 between 93 km and the peak of flight at 131 km. Mass 46 was predominant, the relative abundances being approximately 96.5, 1.6, 0.2, 1.0, and 0.7 in the order of decreasing mass. In both flights mass number identification was unambiguous and checked calibrations within ±0.5 AMU. There was no indication of positive ions on this daytime flight. Assuming equal collection properties for the two spectrometers other positive and negative ions, on both flights, would have been detected if their concentration had been as much as one per cent of the most prominent ion detected.

H. Freeborn Johnson (7205 Ridgewood Ave., Chevy Chase 15, Md.) *Late Annual Values at World Geomagnetic Observatories.* The observers-in-charge at world-wide geomagnetic observatories have been assiduous in supplying annual values of declination (D), horizontal intensity (H), and vertical intensity (Z). The values are either final or preliminary, or additive to, or revisions of those previously published in the *Journal of Terrestrial Magnetism and Atmospheric Electricity* and its continuation *Journal of Geophysical Research.* Data for 1955 have even been kindly forwarded.

Joseph Kaplan (U. S. National Committee for IGY, Washington, D. C.) *Main Aspects of the IGY Program.* A brief description of the origin and development of the International Geophysical Year program is given. Some of the international aspects of scientific cooperation under the program are discussed with illustrative examples of how such cooperation enhances the value of certain selected experiments. United States contribution to the planning and execution of some joint undertakings is described in more detail, and special reference is made to World Archives and Data Centers which will serve to accumulate source material and make it accessible to scientists of all participating nations.

W. W. Kellogg (The Rand Corp., Santa Monica, Calif.) *Suggestions for Measuring the Circulation in Polar Regions in the Upper Atmosphere by Indirect Methods.* There is good evidence for the fact that air converges over the polar regions at high altitudes in winter. This results in a variety of effects, such as increased total ozone in the stratosphere, intermittent subsidence in the region of the tropopause, and subsidence and warming in the region of the mesopause (60–90 km). There may be an important effect on the lower atmospheric circulation due to this polar convergence, and, in order to get more information on the relationships between the synoptic situation and the circulation in the stratosphere and mesosphere, it will be necessary to make systematic observations on parameters which are related to this circulation. Ozone distribution and the radiative temperature of the ozone layer are promising parameters, and can be measured from the ground. The temperature in the mesopause region can be estimated from studies of OH or possibly O emission.

John A. Knauss (Scripps Institution of Oceanography, La Jolla, Calif.) *Some GEK Observations of the Equatorial Countercurrent in the Eastern Pacific.* The Equatorial Countercurrent in the eastern Pacific has been observed by GEK and BT observations on the Shellback and Eastropic Expeditions of 1952 and 1955. The transient character of its circulation is described and the validity of GEK observations in these latitudes discussed. Plans for future work on the Countercurrent during the IGY is described.

L. Knopoff and A. F. Gangi (Institute of Geophysics, University of California, Los Angeles, Calif.) *The Scattering of Surface Wave Motions by Topographic Irregularities.* A three-dimensional seismic model of Lamb's problem with an irregular boundary has been used to study the scattering by topography of wave motion in the surface. The scattering may be interpreted in terms of four types of interactions at the obstacle. These are the types P-P, R-R, P-R, and R-P. The last two of these have been reported by Tatel and interpreted to be the cause of much of the seismic noise. The P-P and R-R interactions are studied here in detail. The P-P and R-R interactions are in most cases the most prominent features of a seismic scattering record, more so than are the conversion types. The P-P interaction is generally observed as an amplification and a mild phase shift of the P wave arriving at the receiver. The R-R interaction is, on the other hand, an attenuation and phase shift of the Rayleigh wave. The scattered P wave is in phase with the incident P wave; the scattered Rayleigh wave is out of phase with the incident R. For a cylindrical obstacle, the disturbance increases with diameter and is a maximum when the height is about one-fourth wave length and the obstacle lies directly between source and receiver. Surface scattering is strongest in the forward direction. Reciprocity has been observed for all four interaction types.

M. J. Koomen, R. Scolnik, and R. Tousey (Naval Research Laboratory, Washington 25, D. C.) *Night Airglow Emission Layers Observed from a Rocket.* Photometers designed to measure the altitude and intensity of the 5577A and the 5890-6A airglow emission lines, and the airglow background at 5300A were flown in a rocket on December 12, 1955. Each photometer consisted of an RCA 1P21 multiplier phototube especially selected for high sensitivity, a lens and aperture system to limit the field of view to five degrees, and a multilayer interference filter of 20A band width to isolate the wanted spectral region. Current from each phototube was fed into an amplifier employing a single miniature electrometer tube. The amplifier output was telemetered to ground. The preliminary results indicate that the 5577A and 5890-6A emissions arose in layers which were remarkably similar. The centers of the layers were within the altitude range 85–95 km. A large part of the 5300A radiation also originated at approximately this altitude. There was no measurable 5890-6A emission above 110 km. The 5577A layer appeared to be 0.9 traversed at 110 km; a small residue persisted to higher altitudes, possibly even up to 141 km, the peak of the

trajectory. The bottom of the layer for all three wavelengths was in the neighborhood of 75 km.

JAMES H. KRAAKEVIK (Naval Research Laboratory, Washington 25, D. C., and University of Maryland, College Park, Md.) *Conductivity and Conduction Current Density in the Troposphere.* Simultaneous fair-weather measurements of both polar conductivities and the conduction current density have been made from a P4Y aircraft up to an altitude of 20,000 ft over a number of land and ocean areas in the northern half of the western hemisphere. The altitude dependence of the conduction current density is presented, showing the influence of convection in the vertical transport of charge within the exchange layer. The variation of the ratio of negative to positive conductivity with altitude is presented and interpreted. Geographic variations and diurnal variations in Greenland of the columnar resistance and current density are described.

W. C. KRUMBEIN AND H. A. SLACK (Northwestern University, Evanston, Ill.) *The Relative Efficiency of Sampling Designs for Sedimentary Particle Populations.* An experimental study was conducted to determine relative efficiency of six sampling designs in estimating mean particle size, average mineral composition, and other sedimentary attributes. The designs each involved independent collection of 16 samples from a 300 x 300 ft segment of Lake Michigan beach near Waukegan, Illinois. The plan included unrestricted random samples and sets of systematic, stratified, and clustered samples. In terms of the fixed number of samples in each set, it was found that when the sedimentary attribute was distributed in a homogeneous manner over the beach there was little difference in relative efficiency of the several designs. On the other hand, when strong sedimentary gradients were present, stratified sampling gave optimum results. Inasmuch as mean particle size shows significant changes across many beaches, the implications of the study are that stratified sampling is to be recommended when the objective is estimation of the particle-size population mean. However, when the gradients themselves are the object of study, it is desirable to collect systematic samples in a grid. Both objectives can be met by selection of a design that combines grid sampling with additional samples in the most variable sampling strata.

G. KULLERUD AND H. S. YODER (Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.) *Upper Stability Curve of Pyrite.* The upper stability curve of synthetic pyrite has been found to pass through the following points: 690°C, one bar sulfur pressure; 730°C, 335 bars; 745°C, 1000 bars; 760°C, 2000 bars; and 815°C, 5000 bars. The general reaction taking place at this univariant equilibrium curve may be formulated: Pyrite $\rightleftharpoons$ pyrrhotite + sulfur. Pyrite grows as pale brass-yellow crystals which exhibit predominantly the cubic and octahedral faces. The powder x-ray diffraction pattern of synthetic pyrite (a = 5.419 A) is identical to that of natural pyrite. Pyrrhotite occurs as black, magnetic crystals having a hexagonal prismatic habit. The composition of the pyrrhotite determined by an x-ray method is $Fe_{1-x}S$, where x is close to 0.1. The sulfur appears white to light yellow and, when observed at room temperature, is of the orthorhombic form. The occurrence of primary pyrite in gabbros and granites and not in basalts and rhyolites is accounted for by comparing the upper stability curve of pyrite with the beginning of melting curves of rocks of basaltic and granitic compositions. As seen from the small increase in stability of pyrite with pressure, these general relationships also hold for sulfur pressures much less than the total pressure.

J. LAURENCE KULP AND WAYNE U. AULT (Lamont Geological Observatory, Palisades, N. Y.) *Sulfur Isotope Variations in Hydrothermal Sulfides.* The relative abundance of the sulfur isotopes has been measured on a large number of hydrothermal sulfides. The isotopic ratio of S^{32}/S^{34} varies by seven per cent in all samples. The ratio in meteorites is constant and presumably represents the average of terrestrial sulfur and the present sulfur isotope composition in the mantle. Many mines show consistent sulfur isotope ratios, but from district to district the ratios may be higher or lower than mantle sulfur. This is interpreted to mean that most hydrothermal ore solutions originate in the crust rather than the mantle and that the particular isotope ratio obtained depends largely on the ratio of original sedimentary sulfate to sedimentary sulfide in the volume element of the crust from which the hydrothermal sulfides are derived. In several areas such as Ivigtut, Greenland, isotope composition of lead is consistent with the sulfur isotope abundance under this interpretation. Transportation and deposition do not appear to give first-order variations in the sulfur isotope ratios.

P. K. KURODA AND B. L. ROBINSON (Department of Chemistry and Department of Physics, University of Arkansas, Fayetteville, Ark.) *Natural Uranium Chain Reaction and the Uranium-Lead Age of Minerals.* An equation has been derived which relates the spontaneous fission rate of U-238, the neutron induced fission rate of U-235, and the U-235/U-238 ratio in uranium minerals. From the experimentally obtained ratio of the neutron induced fission rate to the spontaneous fission rate of uranium in a modern uranium ore, one may calculate a critical age (t_{crit}), that is, the time when the chain reaction becomes critical in the mineral. The value of t_{crit} = 1500 $\pm$ 300 million years thus obtained for Great Bear Lake pitchblende is in most remarkable agreement with the published Pb-207/Pb-206 age of this mineral, which lie between 1330 and 1430 million years. The lower limit of the critical age for the rare-earth-rich minerals (t_{crit} = 2850 million years), calculated from the experimental data of Fleming and Thode, is similar to the convergent ages of Ahrens (t_{conv} = 2680 to 2800 million years) for the most primitive monazites and uraninites.

VINCENT E. LALLY, ROBERT F. MYERS, AND DONALD H. MCINNIS (Air Force Cambridge Research Center, Bedford, Mass.) *Information Content of Weather Charts.* A technique for computing the information content of simple line sketches is presented. The technique is extended to analyzed weather charts. A description is given of the 'incremental weatherplotter,' a device which will transmit weather charts at five times present facsimile speed, in color, and on any arbitrary map size up to 30 x 40 inches.

H. E. LANDSBERG (U. S. Weather Bureau, Washington 25, D. C.) *The Data-Processing Problem in Meteorology.* Meteorology, in common with other geophysical sciences, collects and accumulates vast amounts of data. The rate is about 10^8 observations per year. In some subfields and on an areal basis still more are desired. The revolutionary impact of automation has brought about new procedures in synoptic meteorology and

climatology. We still need much evaluation and planning. The symposium will present many phases of this theme and explore the ramifications in the discussion. Among the important questions are: How much information do the data contain? How much and in what form should the data be procured, processed, and ultimately stored? What is the recall value of the observations?

JEAN T. LEE AND JOSEPH G. GALWAY (U. S. Weather Bureau, Washington 25, D. C.) *Preliminary Report of the Relationship between the Jet at the 200-mb Level and Tornado Occurrence.* In a study of the 200-mb Height Chart and associated jet to determine their usefulness in tornado forecasting, a consistent phenomenon was observed, namely, that the majority of tornadoes investigated occurred along or near the −60°C isotherm at 200 mb. More precisely, the western and southern portions of the −60°C isotherm of the cold 'pool' it circumscribed was the favored area. The jet at 200 mb in most cases delineated that portion of the −60°C isotherm under which tornadoes occurred. Further, certain consistencies appeared on the tropopause chart that might be related with tornado occurrence.

DALE F. LEIPPER (Agricultural and Mechanical College of Texas, College Station, Texas) *Sea Temperature, Statistics, and Shallow-Water Tidal Currents.* The nature of tidal currents in shallow water is indicated by statistical analyses of sea-temperature data. These data are collected at coastal locations which are exposed to the tidal migration of cold water masses. The frequency distributions of sea temperature are influenced by the presence of two different water masses. Each water mass probably has a normal frequency distribution of temperature values about the smooth curve showing the annual variation. Statistical means are used to analyze the variations and a chart is computed showing the probability of observing different temperature values on any certain day of the year.

LUNA B. LEOPOLD AND M. GORDON WOLMAN (U. S. Geological Survey, Washington 25, D. C.) *Stream-Channel Erosion.* The width of a river increases downstream with increasing discharge in a consistent manner as the square root of dominant discharge. Rivers of the same discharge differ in width depending, probably, on type of bed and bank material. As a river migrates across its flood plain, channel dimensions are maintained. This implies that, except through geologic time, channel movement in most streams consists of trading of material. Without changes in discharge, channel erosion, then, cannot generally be a source of sediment except when the river impinges on a terrace or bluff having a height above the modern flood plain. Bed degradation and aggradation are usually of greater importance as a source of sediment than changes in channel width. Extreme degradation is common in places in the semi-arid West and in the Southeast, but channels may scour or fill, as in some stations on the Rio Grande, without much net change in cross section over a period of years. Erosion produced by large floods such as those of August, 1955, in Connecticut, is highly variable. The relative importance of material, vegetation, channel flow patterns, and seepage in bank erosion is known only in a qualitative way. Preliminary measurements in Maryland suggest that bank recession is related to fluctuations in water stage and to freezing and thawing of the bank material.

MYRON G. H. LIGDA (Texas A and M College, College Station, Texas) *The Utilization of Radar Observations in Weather Analysis.* Comparison of radar observations covering large areas with corresponding surface and upper air maps has shown in a number of cases that conventional synoptic analysis often does not provide an adequate description of many weather conditions of vital concern to forecasters. Examples are presented of actual situations where timely radar observations would have greatly aided the forecaster in the location of areas of severe weather, determining the extent, velocity, and stage of development of squall lines, and evaluation of the relative severity of weather conditions along extended fronts. Methods for the collection and dissemination of radar storm observations over large areas are suggested.

H. A. LINTNER, D. ATLAS, AND R. WEXLER (Harvard University, Milton 86, Mass.) *Characteristics of Severe Storms as Seen by the AN/CPS-9 Radar.* A few cases of severe storms, as detected by CPS-9 radar, have been analyzed with respect to maximum echo intensity, maximum heights, hooks or appendages, and location of hail reports. Preliminary results show a tendency for the hail to be located at or near maximum echo intensity downwind from the appendages and upwind from the echoes of maximum height. While striking echo appendages were associated with the presence of hail in two of the most severe cases, such a feature is not a sufficient indication of hail.

GEORGE A. LLANO (Research Studies Institute, Air University, Maxwell Air Force Base, Ala.) *Botanical Research Essential to a Knowledge of Antarctica.* Most of our information about the flora of Antarctica is derived largely from piecemeal collections made by members of about 20 expeditions. Their botanical work was usually limited in space and time to local areas, and represented a small fraction of their interest and effort. Above all, collections were made by scientists ill-acquainted with the type of vegetation indigenous to the Antarctic. The flora of Antarctica is preponderantly cryptogamous, and these plants besides being inconspicuous are an unfamiliar and difficult subject for most botanists. Coordinated and planned research by a trained cryptogamist is not only likely to extend the existing list of 60 mosses and some 300 lichens but is also likely to make significant strides in ecology and in intrapolar and intercontinental distributional patterns. Knowledge is also needed about the relationship of the present vegetation to ice and snow terrain and ice fluctuations. In conclusion, this research may permit ventures into the more fundamental and enigmatic problems of origin, age, and dispersal. In botany there is no substitute for the study of a natural, living population.

LESTER MACHTA (U. S. Weather Bureau, Washington 25, D. C.) *The Application of Gummed Films for the Collection of Settled Particulates.* Gummed films have been successfully employed in a U. S. Atomic Energy Commission-U. S. Weather Bureau radiological fallout network in the United States for several years. Although the mechanism of collection during precipitation is uncertain, the paper appears to collect, with reasonable success, the radioactive particles which are scavenged by the raindrops. Collection efficiencies during dry weather are probably a function of atmospheric turbulence. Comparisons with 'standards' will be offered. The variability of data according to the distance between stations can be used to determine the spacing between stations to avoid missing fall-out of a given

intensity after one specifies a probability that this should not occur.

THOMAS F. MALONE (Travelers Insurance Co., Hartford, Conn.) *The Role of Probability in the Communication of Weather Information.* The question of semantics in the issuance of weather information is considered in relation to the more general problem of communications between the forecaster and the uses of the forecast. The problem of communications is discussed from two points of view: the inherent nature of the prediction problem, and the ultimate application of weather forecasts. It is concluded that there is a basic indeterminacy in weather prediction which precludes the possibility of precise categorical forecasts within the foreseeable future. It is also concluded that the application of weather forecasts is to an operational decision of one kind or another. In communication, then, cognizance must be taken of this indeterminacy in a way that will optimize the usefulness of the forecast in making these decisions. This leads directly to probability forecasts. Some experience with an elementary type of probability forecast is summarized. It is suggested that some of the semantic difficulties can be alleviated by issuing forecasts couched in probabilistic terms.

HUGO MANDELBAUM (Wayne University, Detroit, Mich.) *Evidence for a Critical Wind Velocity for Air-Sea Boundary Processes.* W. H. Munk [1947] deduced from various evidence the existence of a critical wind speed at $V = 660$ cm/sec at which laminar flow at the air-sea boundary changes into turbulence. G. Neumann [1951] argues against its existence, while H. U. Roll [1952] sides with Munk but expects the critical speed to be different in the open sea and in coastal waters. For the present study 5000 simultaneous wind and current observations at Amrum Bank Light Ship were divided into eight wind-velocity groups (Beaufort scale) and subjected to harmonic analysis to yield a residual current which can be considered as exclusively wind-driven. The current velocities W, when plotted against the wind velocities V in cm/sec, show a definite discontinuity between the wind-velocity Groups 1 to 4 and 5 to 8, that is, at V between 600 cm/sec and 650 cm/sec. The lower group shows a strong linear relationship $W = c + kV$, while the upper group indicates a relationship $W = f(\sqrt{V})$. There is a pronounced reduction in current speed between Groups 4 and 5. The discontinuity and the slower increase of W at higher V might be explained by a dissipation of energy in turbulent flow.

H. T. MANTIS AND F. OHNSORG (University of Minnesota, Minneapolis, Minn.) *The Significance of the Intermediate-Scale Motions Observed with a Constant-Altitude Balloon.* The velocity spectra determined from trajectories of constant-level balloons in the upper troposphere have repeatedly shown a high power for motions with periods of from one to several hours. These intermediate-scale motions are separated from the motions at the high frequencies associated with surface turbulence by a plateau of relatively low power. In some longer flights these motions can be distinguished from the motion of synoptic scale. A detailed investigation of several well-documented balloon flights has been made in which the trajectory was compared with the observed pressure fields using the energy and momentum equations. The overall kinetic energy change in periods greater than three hours corresponds reasonably well with the number of smooth contours crossed. The trajectory derived as a solution to the momentum equation using the same smooth contours, however, differs markedly in the amount of acceleration predicted. It is possible to reconcile the results of the two comparisons with the pressure field and be consistent with the observations of the velocity spectrum by postulating intermediate-scale pressure disturbances which are correlated with the air motions.

ELWOOD MAPLE (Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Mass.) *Geomagnetic Fluctuations at Frequencies of Three to 45 c/s at Point Barrow, Alaska.* About one month's data on geomagnetic fluctuations in the sub-audio-frequency range of three to 45 cps were obtained at Point Barrow, Alaska, in the fall of 1952. The amplified output of a detector coil was recorded on magnetic tape. At playback, the signal was filtered, and average values of fluctuation strength were obtained for each of five frequency bands. This work was done while the author was at the U. S. Naval Ordnance Laboratory.

The results indicate that the largest fluctuations throughout the frequency range are associated with magnetic activity as measured by the K index. The present data are not sufficient to define quantitatively the nature of this relationship, which does not appear to be a simple one.

The most interesting feature of the results is that the largest sub-audio-frequency fluctuations tend to occur several hours before the large magnetic disturbances ($K \geq 7$). One occurrence of this type at a low latitude has been reported by Aarons. The present data indicate that the phenomenon is much more common in the auroral zones. Some implications of the data concerning the possible particle-radiation origin of the fluctuations will be discussed.

H. J. MASTENBROOK (Naval Research Laboratory, Washington 25, D. C.) *Utilization of Transosonde Data.* The Transosonde System consists of a balloon-borne meteorological station, controlled to float for extended periods along a constant pressure surface. The System represents a new approach to meteorological collection which places emphasis upon the flight trajectory of a balloon along a constant pressure surface as a primary form of meteorological data.

ALBERT MILLER AND HANS A. PANOFSKY (Pennsylvania State University, University Park, Pa.) *Large-Scale Vertical Velocities and Weather, January, 1953.* Vertical velocities determined by the kinematic and adiabatic methods for January, 1953 are compared with those computed by NWP and vorticity techniques. The results lead to conclusions regarding non-adiabatic and frictional effects. The effect of all types of vertical motion on the probability of certain weather types is estimated with dewpoint depression as another independent variable. As control, the same experiment is repeated with meridional wind component at 10,000 ft replacing vertical motion.

ROBERT L. MILLER (Dept. of Geology, University of Chicago, Chicago, Ill.) *Speculation on Water Currents in a Black Shale Environment by Use of Orientation and Dispersion of Fossil Fragments.* The distribution of fossil wood and vertebrate and invertebrate organisms has been recorded in great detail at several levels in an exposure of the Mecca black shale of Pennsylvanian age by R. Zangerl and E. Richardson. The writer has analyzed the distributions statistically to determine the presence or absence and direction of water currents. The measurable properties considered are (1) the orientation

of elongate fragments such as wood, Lystrocanthus spines, and straight cephalopods, and (2) the dispersion in a plane of the above fragment types plus Petrodus dermal denticles and the crustacean-like Phyllocarid. Several models were used for the statistical analysis of the dispersion over a plane, since certain types of fragments were thought to be introduced into the sediment in initial clumps, and other types introduced as independent individuals. The orientation study also presented a special problem because there was no meaningful reference azimuth available. Finally, some inferences are drawn as to current velocity during time of deposition for the three major stratigraphic subdivisions of the exposure.

Robert F. Myers and David G. Rhoades (Air Force Cambridge Research Center, Bedford, Mass.) *Telemeteorology*. The concept of automatically gathering, disseminating, and processing data in a Weather Information Telemeter System (WITS) and its potential effect on operational meteorology are discussed. The ability to use newly developed sensing elements to produce an output in any numeric code form and to furnish data for local, climatological, and synoptic use are stressed in the design of the WITS station described.

M. Neiburger (Air Pollution Foundation, Los Angeles, Calif.) *Wind-Trajectory Studies of the Movement of Polluted Air in the Los Angeles Basin*. The trajectories of the air arriving at various sampling stations at times of peak concentrations of pollutants and peak values of smog effects were computed from observed surface winds. To the extent that these winds represent the actual movement of the pollution from these sources they show that in many cases the pollution could not have come from refineries or other industrial sources. Thus, the evidence from wind trajectories tends to confirm the conclusion drawn from other evidence that automobile exhaust plays an important role in Los Angeles smog. In addition to the trajectories computed backwards from locations of peak pollution concentrations, trajectories were computed forward from possible source areas for both smoggy and random days. The frequency with which the trajectories from these typical sources reached various sections of the Los Angeles Basin was evaluated. The trajectories from refinery areas on smoggy days reached typical residential areas in the northern and western portions of the basin at most 58 pct of the time, again leaving a large proportion of the cases of smog to be explained by other sources.

Gerhard Neumann (New York University, New York, N. Y.) *On the Mutual Adjustment of the Horizontal Field of Mass, the Sea-Surface Topography, and the Level of No Motion in the Gulf Stream*. The paper deals with the development of a layer of no motion for the Gulf Stream in a baroclinic fluid. It is shown why the variable depth of the lower boundary of a current plays an important role in the analysis of ocean currents. One of the *Allantis* sections between Chesapeake Bay and Bermuda is used to test the theoretical relationships between the depth of the layer of no motion, the topography of the sea surface, and the horizontal density distribution.

Chester H. Page (National Bureau of Standards, Washington 25, D. C.) *Some Proposals for Redetermining the Acceleration of Gravity*. Several modernized versions of classical schemes for measuring the acceleration of gravity have been proposed for use in a redetermination. The advantages of electronic timing systems are evident.

The National Bureau of Standards is considering a modification of a free-fall experiment proposed at the National Physical Laboratory (England), and a locally suggested new type of pendulum experiment. The precision in the falling ball scheme depends upon optical diffraction phenomena, which are being investigated. The pendulum scheme avoids knife edges by using a round shaft for a bearing, and reducing friction by driving the shaft with a servo-mechanism to reduce relative motion. Advantages and pitfalls of these schemes will be discussed.

Erik H. Palmen and Herbert Riehl (University of Chicago, Chicago, Ill.) *On the Balance of Absolute Angular Momentum in Tropical Storms*. The balance of absolute angular momentum in tropical storms is calculated using the mean upper-air wind structures of these storms. The frictional stress computed at the surface is compared with that determined from other approaches; reasonable agreement is obtained. Further, the heat balance is calculated and necessary relations between flow of heat and momentum for maintenance of steady state are discussed.

Sverre Petterssen (University of Chicago, Chicago, Ill.) *An Experiment in Construction of Prognostic Charts*. During the period January 10 to February 21, 1956 an experiment was made to combine the results of graphical integrations for the 1000- and 500-mb surfaces with conventional forecasting techniques to obtain prognostic charts on a routine basis. The results indicate that the graphical technique is definitely useful as a first approximation, and that considerable refinements can be added by application of supplementary techniques.

G. L. Pickard and R. W. Trites (University of British Columbia, Vancouver, B. C., Canada) *Heat Budget Study for British Columbia Inlets*. Fresh water entering the British Columbia inlets moves seaward, mixing with and entraining salt water from below. A new method, based on a heat budget analysis, is developed to determine the mean seaward movement of the brackish layer. The method is also applied to gain information on the mixing process and to determine the depth from which salt water is entrained into the surface layer. The results for mean transports are found to be in good agreement with those derived from other methods. The method offers some distinct advantages over direct methods for determining fresh water inflow and circulation since results can be obtained quickly, with little effort, and without the necessity for anchoring a ship.

Frank Press (Seismological Laboratory, California Institute of Technology, Pasadena, Calif.) and Maurice Ewing (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *A Mechanism for G-Wave Propagation*. G waves are pulse-like horizontally polarized shear waves, with breadth of about 60 sec, generated by certain large-magnitude earthquakes. They are essentially free from dispersion effects, showing only slight modification of the wave form after two circuits of the Earth. It is suggested that the decrease of shear-wave velocity with depth in the upper mantle produces curvature in the propagation path sufficient to minimize or eliminate reflections in a spherical shell sufficiently wide to accommodate waves 300 km long. The speed of 4.7 km/sec established for

Sn in refraction studies indicates a thin mantle layer bounded by the *M*-discontinuity.

The phase *G* provides independent evidence for a reversed velocity gradient in the upper mantle and the pulse shape is simply related to the motion at the focus. The phases S_A and P_A are the 'whispering gallery' phases which travel in the thin upper mantle layer by repeated reflections at the *M*-discontinuity.

FRANK PRESS (Seismological Laboratory, California Institute of Technology, Pasadena, Calif.) *Crustal Structure Determined by the Phase-Velocity Method.* Local changes in crustal structure may be deduced from variations of phase velocity of surface waves. Model seismology experiments are used to demonstrate this method of exploration. Variations in Southern California of phase velocity of Rayleigh waves from trans-Pacific earthquakes are interpreted as indicating (1) normal crustal thickness in the Peninsular Range Province, (2) increase of mean crustal thickness by about 50 pct in the Sierra Nevada block, and (3) decrease in crustal thickness by as much as 50 pct in the continental borderland. *Lg* velocity studies for California paths support the correlation of phase-velocity variations with crustal thickness changes rather than elasticity changes.

H. RIEHL AND D. FULTZ (University of Chicago, Chicago, Ill.) *Structure of Long Waves and Jet Stream in a Steady Three-Wave Dishpan Experiment.* Photography of surface flow in a steady three-wave dishpan experiment plus temperature measurements at various depths, radii, and longitudes permit determination of the three-dimensional temperature and pressure distribution, also of geostrophic wind and vorticity. The structure of long waves and jet stream with respect to these variables is presented in chart and cross-section form, also the flow of water relative to the fields of wind speed and vorticity. Vertical motions are computed in the interior of the dishpan with the isothermal assumption. The distribution of vertical motion and the fields of divergence is shown, also the surfaces of nondivergence. The vertical circulation relative to the jet stream is calculated. All quantities (except temperature) are given in non-dimensional terms for comparison with the atmosphere. It is demonstrated that the degree of similarity is very great and goes well beyond what might be expected.

M. N. E. RIFAI, WARREN J. KAUFMAN, AND DAVID K. TODD (Division of Civil Engineering, University of California, Berkeley 4, Calif.) *Dispersion Phenomena in Laminar Flow through Porous Media.* When a perfect tracer substance is introduced into a seepage or ground-water flow system, the concentration of the tracer varies with distance and time. The mechanism and parameters affecting this dispersion phenomenon are studied theoretically and experimentally, the latter by means of a tracer displacing a fluid saturating a sand column. Microscopic variations of the fluid velocity and molecular diffusion are assumed to be governing factors. For analytic purposes a porous medium is treated (a) as a group of variable diameter capillary tubes and (b) as a completely disordered group of sand particles. Expressions for the effects of velocity variations and molecular diffusion on the tracer concentration are derived for each case. Comparison of theoretical and experimental volume-concentration curves suggests that the effect of microscopic velocity variations greatly exceeds that of molecular diffusion.

VAUGHN D. ROCKNEY (U. S. Weather Bureau, Washington 25, D. C.) *Radar Observation of Middle East-Coast Hurricanes.* Radar observational data gathered at Hatteras, N. C., during hurricanes Connie, Diane, and Ione are presented. Similar and dissimilar characteristics of these storms and of Edna of 1954, as observed by radar, are discussed.

ALLEN S. ROGERS AND JOHN H. FETH (U. S. Geological Survey, Salt Lake City, Utah) *Radon Surveys Applied to a Specific Hydrologic Problem.* The Weber River near Ogden, Utah, increased in flow, at low stage, from 2.8 to 7.5 ft^3 per second within a distance of 1.5 miles. The only visible additions to streamflow occurred at two points where small springs contributed perhaps 20 gallons per minute. The problem was to locate the major increments of streamflow increase and to determine whether the water represented influx from bedrock or ground water from bank storage. Intermediary stream gaging was impossible because of the abundance of large boulders in the stream channel. A radon survey was made of stream and related spring waters, based on the following premises: (1) that ground water generally contains more radon than surface water; (2) that the introduction of a relatively large amount of ground water into a small turbulent stream causes an abrupt increase in the radon content of the stream water; (3) that the rate of radon dissipation into the atmosphere is an exponential function with respect to distance of streamflow. The results showed that abrupt increases in the radon content in the stream (as much as 200 micromicrocuries per liter) occurred at four points, two of which were associated with the visible springs (radon content 500–750 micromicrocuries per liter). The high radon concentrations (points of ground-water influx into the stream) seem to be related to bedrock features rather than to large areas of alluvial material, indicating a bedrock control for ground water in this area. Increments of streamflow, which were estimated from radon concentrations in stream and related spring waters, accounted for 65 pct of the total observed increase in streamflow in this reach of the Weber River. Similar calculations using data from chemical analyses yielded comparable results.

FINN RONNE (Captain, USNR, 6323 Wiscassett Road, Washington 16, D. C.) *The Weddell Sea Area.* The Weddell Sea area is considered here as one possessing high strategic importance for exploration and study in connection with the IGY program. Tentative plans are presented for United States ships to penetrate severe pack-ice conditions and establish a base, giving full consideration to current Weddell Sea activities by Argentine and British parties. The historical background is considered and the potential scientific and geographical (political) gains are weighed.

JOHN ROSCOE (General Staff, U. S. Army, Washington 25, D. C.) *Antarctic Photogeography.* The employment of air-photo analysis as a geography research technique is termed photogeography; those skilled in this practice are called photogeographers. In Antarctica, the only continent where the existing aerial photographs contain more geographic and related information than do the maps and publications extant, aerial-photo analysis assumes an unusually significant importance. Since the first aerial photographs were

made in 1901 by Scott and von Drygalski, approximately one-fifth of the continent has been photographed, but only a small portion of the area covered has been examined by surface parties. This photography forms a permanent record of the Antarctic landscape at a given time since the area is one of extremely limited accessibility; a significant portion of what is to be learned about the Antarctic must come from this source.

Antarctic aerial photographs have five prospective uses, all of which will be important to IGY scientists. They are: (1) illustration, (2) map making, (3) accessibility studies, (4) detailed area studies, and (5) detailed functional studies (for example, glaciology, morphology, geology, place names, climatology, zoology, oceanography, and aurora and airglow). The status, value, and prospects of Antarctic photogeography are discussed.

A. E. SCHEIDEGGER (Dominion Observatory, Ottawa, Canada) *Correlation Tensors in Statistical Hydrodynamics in Porous Media.* Statistical mechanics has proven to be very successful in various branches of geophysics, such as in the study of turbulent motion of the atmosphere and in the study of ground-water flow. Thus, the occurrence of dispersion of the individual particles during laminar flow in porous media has been interpreted by Yuhara [1954] as analogous to the fluctuations of velocity during eddy motion in turbulent flow of bulk masses of fluid.

The statistical theory of flow through porous media has been criticized for using a different approach from the statistical theory of turbulence, notably because velocity correlation tensors had not been introduced as dynamical variables. It is shown in the present paper that the velocity correlation tensor, a significant dynamical variable in turbulence, is unsuitable as such a variable in flow through porous media. It depends only in a trivial way on the pressure term. It does depend, however, on the geometry of the porous medium and is thus suitable to characterize the latter rather than the flow through same. It thus appears that the analogy between turbulent flow and flow through porous media is not very complete in spite of the fact that the contrary has been claimed.

JOHN J. SCHULE (Applied Oceanography Branch, U. S. Navy Hydrographic Office, Washington 25, D. C.) *Comparison of Sea-Ice Conditions in the American Arctic, 1953–1955.* The U. S. Navy's extensive aerial ice reconnaissance and forecasting program has provided adequate data on which to base a comparison of sea-ice conditions in the American Arctic for the past three years. Stress is placed on how qualitative descriptions such as a 'good' or a 'bad' ice year at specific localities become misleading when applied to an entire region such as the American Arctic.

A. H. SHAPLEY (National Bureau of Standards, Central Radio Propagation Laboratory, Boulder, Colo.) *Clues to Ionospheric Conditions in the Southern Auroral Zone.* While there is a considerable amount of experience with short-wave radio communication via the ionosphere from the many Antarctic expeditions since at least 1928, quantitative determinations of ionospheric parameters exist for only a few places and for relatively short periods of time. From sweep-frequency vertical-sounding observations at Adelie Land, Port Lockroy, Deception Island, Campbell Island, and Macquarie Island, and near Little America, some indication can be found with regard to north-south correspondence of electron concentration, heights, and degree of homogeneity of the ionospheric layers. The radio communication data can be used as a rough check of the consistency of these results, but the operation of a rather dense network of stations during IGY will be needed for any real description or understanding of these phenomena.

ROBERT P. SHARP (California Institute of Technology, Pasadena, Calif.) *Objectives of Antarctic Glaciological Research.* Antarctic glaciological studies should focus principally upon features unique to the region and upon relations of world-wide significance. Antarctic ice is the greatest mass of land-locked water substance on Earth, and determination of its volume by geophysical means is needed to complete a world water inventory. Return of even a part of this water to the oceans has far-reaching geological and economic significance. Data on the past, present, and future behavior of this ice will therefore be sought through studies of accumulation and wastage, of firn stratigraphy, of geological evidence for ancient fluctuations, and of pertinent glacio-meteorological factors. Identification of annual accumulation layers is essential, and oxygen isotope ratios (O^{18}/O^{16}) promise to be useful for this and for indicating the nature and magnitude of earlier climatic variations.

Deep drill holes in the Ross Ice Shelf and the inland ice will give valuable data on thermal regime and on the diagenetic changes converting snow to glacier ice in this cold environment. Crystal fabrics in cores from these holes bear significantly upon the basic problem of glacier flow.

Investigation of the constitution, structure, and genesis of the Ross Ice Shelf will advance the understanding of ice shelves elsewhere. Finally, every effort will be made to recognize and date, by tritium, radiocarbon, or other means, prominent events in the history of Antarctic ice so that synchronous or nonsynchronous behavior with relation to ice masses in the rest of the world can be established.

JOHN SHERROD (Library of Congress, Washington 25, D. C.) AND H. NEUBERGER (Pennsylvania State University, University Park, Pa.) *Understanding Forecast Terms—Results of a Survey.* The questionnaire technique was used to survey students at the Pennsylvania State University regarding their understanding of forecast terms employed by the U. S. Weather Bureau. A representative sample of 1000 replies was selected for detailed analysis. The students were asked to choose one each of several qualitative terms listed under wind, temperature, precipitation, and cloudiness, and to describe the current weather with one word. The criteria for various forecast terms, based on a majority of the replies, were as follows: 'calm' for winds of less than 5 mph; 'windy' or 'strong' winds for winds above 15 mph; 'cool' for temperatures below 65°F; 'warm' for temperatures above 75°F; 'warmer' for a temperature increase of more than 5°F; and 'cloudy' for conditions of eight-tenths or more low-type clouds. The results further suggested that, for the conditions tested, the weather forecasts could have been adequately expressed by the following terms: fair, cloudy, rain, snow, warm(er), and cold(er).

A. K. SHOWALTER (U. S. Weather Bureau, Washington 25, D. C.) *Stability and Thickness Relationships of Two Adjacent Layers.* The National Weather Analysis Center (NWAC) has found it economical and

practicable to use several interpolation and extrapolation techniques in order to ensure vertical thermal consistency and eliminate excessive duplication of effort. These techniques are based on sampled relationships between thicknesses of adjacent layers. Various combinations of layers have been sampled but most use has been made of the 1000–700 mb and 1000–500 mb ratios. It is believed that much of the high correlation between heights of mid-troposphere pressure surfaces can be explained by the necessary stability control between adjacent layers. In most cases the temperature of the superjacent layer is limited by a lapse rate between the isothermal and the dry adiabatic. This paper presents a convenient solution of the relationship between thicknesses of adjacent layers as a function of the thickness of lower layer and the mean lapse rate between the layers. In effect, the formulas developed are predicted regression equations which can be used to evaluate the statistical tabulations that are being made.

FRANCIS B. SILSBEE (National Bureau of Standards, Washington 25, D. C.) *Importance of 'g' in the Determination of Standards.* Knowledge of the local value of 'g' is an essential link in at least two fundamental types of measurement. The unit of electric current, the ampere, is defined in terms of the force developed between two current-carrying conductors in a specified geometrical configuration. By far the most convenient method for measuring this force is to balance it against the weight, mg, of a known mass, m. It is from the ampere thus determined that other units, watt, joule, oersted, and gauss, are derived. The second application is to use 'g' in measuring the force on a conductor while it is carrying a known current in a magnetic field. This, when combined with the measured resonance frequency of protons when in that field, yields the gyromagnetic ratio of the proton, one of the very fundamental atomic constants.

J. A. SIMPSON (Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago 37, Ill.) *Cosmic Radiation Results from the Antarctic Expedition, 1954–55.* Cosmic-ray studies have been applied to the problem of investigating the distribution of the Earth's permanent magnetic field extending into the interplanetary medium. The equatorial crossings of the USS *Atka* and additional data show that this outer field distribution is strikingly different from the results obtained from geomagnetic measurements extrapolated from the surface of the Earth. The interpretation of these results and their use in defining new magnetic coordinates for extraterrestrial charged particles will be discussed.

S. F. SINGER (University of Maryland, College Park, Md.) *A New Model of Magnetic Storms and Aurorae.* To explain the sudden commencement (SC) of magnetic storms, the SC*, and pre-SC disturbances, we invoke the following model: The solar eruption produces a shock wave which arrives at the Earth 22–34 hours later. High-velocity particles having a smaller interaction precede the shock wave and cause the pre-SC bay-like disturbances at high latitudes. The shock wave itself is retarded by body forces produced by the geomagnetic field, splits and enters the auroral zones. In pushing out lines of force it creates the polar SC* events. Charge separation in the shock waves produces the driving force for the SC currents which flow in the atmosphere (in accordance with Vestine's analysis).

The storm decrease is produced by the high-velocity particles following the shock wave (about nine hours later) which enter because of field perturbations into the normally inaccessible Störmer-allowed regions around the dipole. Here they are trapped and will drift, producing the ring current, which gives rise to the storm decrease. Particles with pitch angle $<2.5°$, however, can reach the Earth's atmosphere and will produce aurora, some of the airglow, and ionosphere disturbances. These particles are replenished by perturbations produced by solar influences having a 27-day recurrence. Many other particles are absorbed or scattered out of the trapping regions so that their number diminishes rapidly in a day or so, as does the magnetic storm decrease.

IRVING A. SINGER AND ROBERT M. BROWN (Brookhaven National Laboratory, Upton, L. I., N. Y.) *The Annual Soil-Temperature Wave at Brookhaven National Laboratory.* The proposal of building a 25-BEV proton synchrotron at the Brookhaven National Laboratory led to the investigation of subsoil temperatures in order to compute the thermal stresses and air-conditioning loads. Soil temperatures at 2.5, 5, 10, and 20 ft are measured at four stations located on a circle having a diameter of 600 ft. The annual wave of temperature approximates the theoretical equation for the propagation of a simple harmonic temperature wave into the soil. Variations at the four locations are studied. The thermal diffusion coefficients have been deduced and compared to other locations. Comparisons of the daily and annual cycle are made.

PAUL A. SIPLE (General Staff, U. S. Army, Washington 25, D. C.) *Antarctic Geography.* The challenging task of unveiling the Antarctic Continent has been greatly aided by the advent of new technologies during the past quarter century. The scientific and material developments which contributed most to the increased capability for polar exploration have been in the fields of transportation, communications, and aerial photo surveying. Advances in sciences and technologies in such fields as atomic energy power and heat, food technology, environmental protection, and shelter improvement have tended to make the concept of protracted occupation of the Continent more tenable for the future. Although currently two-fifths of this five million square-mile continent is yet to be seen for the first time, there is every likelihood that before the IGY draws to a close most of the major geographic discoveries will have been made. Concepts of the Antarctic Continent have gradually improved.

The Continent appears to be a 'siamese-like' juncture of two large land masses. The portion lying mostly in the western hemisphere, conveniently designated West Antarctica, is only about half as large as East Antarctica. The latter is believed to be a massive Precambrian shield superimposed by a great dome of snow and ice, and toward its center reaching in excess of 13,000 ft elevation. The smaller West Antarctica is more folded in character and the ice dome near its center is probably less than 10,000 ft high. Where these land masses come in close contact a high-faulted mountain forms a backbone to the whole continental mass. Between the continental glacial domes and these high mountains, natural troughs tend to channel katabatic surface winds off the Continent.

During the forthcoming IGY, glacial and seismic programs will add greatly to our knowledge concerning

the thickness of the ice cap and the surface beneath. Not only will we have a more reliable concept of the Continent but it is likely that the Antarctic will never again be unpopulated even though the geopolitical rivalry for national territorial claims will no doubt continue for many years to come.

DWIGHT D. SMITH (620 S. Glenwood St., Columbia, Mo.) AND WALTER H. WISCHMEIER (Lafayette, Ind.) *Sheet Erosion.* This paper discusses the two principal processes by which sheet erosion occurs and the six factors which effect the magnitude of the losses. The processes are raindrop impact and transportation of soil particles by flowing water. The factors are length and per cent slope, cropping, soil, management and rainfall. The relative effectiveness of each of the three main conservation practices in control of erosion, contour farming, strip cropping, and terracing is presented. The factors and practices are combined in a rational erosion equation for calculating field soil loss for use in application of conservation practices and in assessing land program benefits.

J. L. STEARN AND E. J. PARKIN (U. S. Coast and Geodetic Survey, Washington 25, D. C.) *A Statistical Analysis of Hiran Measurements.* The Hiran electronic distance-measurement system is described, and the problem of defining rejection limits on observations is introduced. A number of samples of actual measurements is analyzed statistically by means of significance tests, and suggestions made for a new approach as to the rejection and acceptance of observations.

DUNCAN STEWART (Carleton College, Northfield, Minn.) *On the Petrology of Antarctica.* Since 1895 over 100 papers have been published relating to the chemistry, mineralogy, petrography, and petrology of Antarctic rocks. Listed are 174 mineral species, subspecies, and varieties, as well as those of questionable occurrence, that have been reported from Antarctica. A number of these have been determined only microscopically, and in the case of gold its presence has been determined only by chemical analysis. Two hundred and thirty-three chemical analyses are tabulated. The chemical analyses are of 15 minerals and 180 igneous, 4 sedimentary, and 34 metamorphic rocks. The rocks encountered are described on the basis of areal distribution.

ARTHUR N. STRAHLER (Dept. of Geology, Columbia University, New York, N. Y.) *Quantitative Analysis of Watershed Geomorphology.* Quantitative geomorphic methods developed within the past few years provide means of measuring size and form properties of drainage basins. Two general classes of descriptive numbers are: (1) linear scale measurements, whereby geometrically analogous units of topography can be compared as to size; and (2) dimensionless numbers, usually angles or ratios of length measures, whereby the shapes of analogous units can be compared irrespective of scale. Linear scale measurements include length of stream channels of given order, drainage density, length of slope orthogonals, basin perimeters, and relief. Surface and cross-sectional areas of basins are length products. If two drainage basins are geometrically similar, all corresponding length dimensions will be in a fixed ratio. Dimensionless properties include stream order numbers, stream length and bifurcation ratios, junction angles, ground slopes and channel gradients, relief ratios, and hypsometric integrals. If geometrical similarity exists in two drainage basins, all corresponding dimensionless numbers will be identical, even though a vast size difference may exist. Dimensionless properties can be correlated with hydrologic and sediment yield data stated as mass or volume rates of flow per unit area, independent of total area of watershed.

J. H. SWARTZ (U. S. Geological Survey, Washington 25, D. C.) *Changes in the Absolute Value of the Earth's Magnetic Field at Kilauea Volcano, Hawaii, between 1952 and 1954.* Measurements of the absolute values of the vertical and horizontal components of the Earth's magnetic field were made at 29 stations around Kilauea Volcano, Hawaii, in August, 1952, and again in August, 1954. The earlier measurements were made during the 1952 eruption. Measurements were made with one vertical and one horizontal magnetometer, using a null method, and were tied into the absolute value for the U. S. Coast and Geodetic Survey's Barber Point Observatory on Oahu by measurements made immediately before and after each survey. The mean values for the vertical and horizontal components were 22,170 and 28,918 gammas respectively in 1952 and 22,154 and 28,909 gammas in 1954. The overall changes were thus small. However, after corrections for secular change, the changes in the vertical component for individual stations were found to range from -56 to $+40$ gammas, and when plotted on a map were found not to be random in their distribution. There was a general decrease in vertical intensity over the Kilauean mass as a whole, in line with the evidence from tiltmeter and other measurements of continuing pressure under the mountain. A zone of positive change was found on the flank of Mauna Loa, and another along the fissure zone through Halemaumau and Kilauea Iki. The largest decrease in vertical intensity occurred at the intersection of an eastern branch of the southwest fissure zone with the Chain-of-Craters zone along which, although farther to the east, the Puna eruption occurred later in 1955.

RICHARD D. TARBLE (4400 Oaklawn St., Bryan, Texas) *Precipitation Patterns by Radar Scope Observations.* Some of the sources of error in rainfall-runoff determination have been caused by the lack of an accurate estimate of the areal distribution of precipitation as well as its intensity. It is the purpose of this paper to show, through theoretical models of known storm types, the areal distribution of precipitation as indicated by radar observations. Various distributions are shown for a simulated drainage area. It is shown that the individual pattern and velocity of the storm must be considered in the evaluation of precipitation distribution over a given area.

HOWARD E. TATEL (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington 15, D. C.) *Gravity Measurements in Alaska and the Yukon Territory.* Supplemental gravity measurements were carried out in conjunction with the seismic expedition of the summer of 1955. Measurements were made along the road north from Valdez and along the Seward Highway of the Kenai Peninsula; along the road and railroad from Haines and Skagway, Alaska, to Whitehorse, Y. T., and beyond. For reduction, at some point, altitudes measured by aneroid altimeter were used.

The greatest deviation from the calculated free-air gravity was measured at Skagway (sea level), -113 milligals. About a third of this could be accounted for by a terrain correction equal to the upward attraction of the surrounding high mountains. There is thus a true

difference from the free-air value of some −80 milligals which represents a deficiency of material below and a net downward stress. East of Valdez, near Thompson Pass, a positive difference between measured gravity and the calculated free-air gravity of +79 milligals was determined. Here a set of early seismic arrivals from shots at College Fiord, 110 km to the east, was found. The gravity differences and early seismic arrivals can be the consequence of the existence there of a buried lens of high-velocity, high-density material, supported by the crust in stress.

HOWARD E. TATEL (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington 15, D. C.) *Seismic Model Experiments.* The three-dimensional model experiments first reported two years ago have been continued. Using surface transmitters and receivers, multiple seismograms of homogeneous (iron) models with surface irregularities have been studied. The patterns obtained simulate those found in field work, and indicate that the conversion process of compression to Rayleigh waves and the converse play a dominant role in the formation of a field seismogram. There are certain small differences in field and model, however, which are described. Scattering conversion from individual surface singularities have been studied.

Models of brass have proven very interesting in that they show patterns similar to those obtained in the field. These have been shown to be due to scattering and are possibly due to efficient conversion-scattering of the high-frequency components of the Rayleigh wave. Studies of buried sources and surface receivers have been carried out. These compare strikingly with recent theoretical work of Pekeris. In particular, there are complex surface wave forms extending in time beyond the shear wave. The surface formed $S \rightarrow P$ wave has been observed, which was first found by Press in a two-dimensional model study. The pattern of $P \rightarrow R$ at a surface singularity has also been studied.

HOWARD E. TATEL AND MERLE A. TUVE (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington 15, D. C.) *Seismic Crustal Measurements in Alaska.* By arrangement with the Office of Naval Research at our request, the U. S. Coast Guard during the summer of 1955 set off nine 2400-lb charges in College Fiord, Alaska, at 61°10.5′N and 147°51.4′W, and thirteen 2400-lb charges near Skagway at 59°28.8′N and 135°21.3′W. The observations centered at College Fiord showed marked differences in different directions. To the southwest on the Kenai Peninsula, the usual upper crustal velocity of 6 km/sec for the compression wave, a critical reflection, and P_n records were obtained, indicating a lower crustal discontinuity at about 34 km (uncorrected for increase of velocity with depth).

To the east, near Valdez, the arrivals were earlier than usually observed. In this region we (Tatel) also measured a marked positive gravity difference of +75 milligals greater than the free-air value. These separate observations could be effects due to a buried lens of high-velocity rock which is held in place by crustal stresses. The data taken in the Yukon Territory from the Skagway blasts indicate relative crustal uniformity. The upper crustal velocity for compression waves is 6.1 km/sec; the depth of the lower crustal discontinuity ranges from 31 to 34 km. One distinguishing feature of the data is the strong set of later arrivals at distances of 200–280 km which are probably reflections from the lower crustal (Mohorovicic) discontinuity. Their arrival times indicate very little increase of velocity with depth.

The striking difference in the two sets of data is further evidence that there are variations in crustal properties over a continental region. It is beginning to appear as if there is 'continental geology.' The expedition was successful primarily because of the enthusiastic participation of our laboratory colleagues.

W. J. THALER AND J. E. MASTERSON (Office of Naval Research, Washington 25, D. C.) *A Rapid High-Altitude Wind-Determining System.* A Loki-type rocket and dart (WASP) fired from a gun-mounted launcher ejected a radar target (window or metalized parachute) at predetermined altitudes where shipboard radar acquired and tracked the target in the wind stream. The rocket launcher was mounted on a 5″/38 gun of a destroyer. By gun elevation and a fixed time fuse in the dart, the burst altitude and position was predetermined such that the director of the gun fire control system readily acquired the target, which was tracked by the radar. Window targets were tracked for 14 minutes in the neighborhood of 114,000 ft. Window and metalized parachute trackings at 60,000 ft and below were correlated with existing soundings with favorable results. Wind speed and direction were read directly from a modified computer in the gun fire control system.

PHILIP D. THOMPSON (Joint Numerical Weather Predicting Unit, Washington 25, D. C.) *A Heuristic Theory of Large-Scale Turbulence and Long-Period Velocity Variations in Barotropic flow.* By combining an equation for the conservation of zonal momentum with the eddy vorticity equation for nondivergent barotropic flow through a channel, it has been found possible to express the time variations of the longitude-averaged zonal wind in terms of the mean zonal wind itself and certain statistics of the eddy velocity field. In large-scale turbulence, where the characteristic dimension of the eddies is comparable with the entire 'width' of the flow, these eddy statistics take on the properties of autocorrelation functions; thus, they depend primarily on the overall scale of the eddies and intensity of turbulence rather than on details of the flow pattern. Changes in the scale and intensity of large-scale turbulence are related to changes in the mean zonal flow through the principles of conservation of total kinetic energy and variance of vorticity. Under a general hypothesis regarding the 'stability' of the eddy statistics, the equations for the zonally-averaged motion comprise a complete system of nonlinear equations, which can be integrated by finite-sum and -difference methods. Accordingly, these equations constitute a mathematical theory of large-scale 'free' turbulence, and provide the basis for a numerical method of predicting the zonally-averaged motion.

With the assumption that the eddy scale is invariant, the equation governing the mean zonal wind takes a form related to that of the classical wave equation. Numerical integrations of this equation verify that extremes of mean zonal wind (for example, pronounced jets) maintain their identity over long periods of time, and migrate either northward or southward (or in both directions at once) in a very regular way, a phenomenon that has been observed by Riehl and Others [1950]. The results also show that a strong jet in the mean westerlies tends to split into two weaker

jets, which then move in opposite directions to produce the separated double-jet structure typical of widespread blocking. The latter has been described as a characteristic denouement from strong zonal flow by Cressman [1949]. The theoretical speed of migration of extremes in the mean zonal wind is found to agree closely with the observed speed in a case where published data are available. Since these features of long-period velocity variations (the most striking and regular discovered to date) have a characteristic time scale of a week or two, numerical prediction methods based on the present theory show some promise of aiding in the preparation of extended-range forecasts.

GEORGE R. TILTON (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) AND CLAIRE C. PATTERSON (Division of Geological Sciences, California Institute of Technology, Pasadena, Calif.) *The Isotopic Composition of Lead in Ultramafic Rocks.* The isotopic composition of lead in three olivine nodules and one dunite has been determined. The results are:

Locality	Source	Pb^{206}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}
Hualalai, Hawaii.....	Nodule	19.29	15.45	37.95
Dreiser Weiher, Germany.	Nodule	19.43	15.30	37.86
San Bernardino, Calif....	Nodule	19.16	15.46	37.78
Twin Sisters, Wash.....	Dunite	19.17	15.61	38.15

Since the accuracies of the ratios are believed to be ± 1 per cent, these leads exhibit no differences which lie outside of experimental errors. The samples contain about 0.01 ppm of uranium and 1 ppm of lead. The U/Pb ratios of the samples at present are too low by a factor of approximately 20 to account for the observed build-up of Pb^{206} and Pb^{207}. Compared to other sources of modern lead, the ultramafic leads contain abnormal amounts of Pb^{206} with respect to Pb^{207} although they do not contain abnormal amounts of Pb^{208} with respect to Pb^{207}.

KARL K. TUREKIAN (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *The Abundance of Cu, Ni, and Cr in Basaltic Rocks.* The emission spectrographic analysis of 150 basaltic rocks from all over the world has been made for Cu, Ni, and Cr. For the first two neutron activation analyses of Smales (1955) on *G*-1 and *W*-1 have been used as checks on accuracy. The agreement is good and gives credence to the revised figures for basaltic rocks as indicating absolute abundance. The variation of the Cr analyses on *W*-1 diabase by various investigations is very small. The technique developed in this investigation agrees with the average of the other investigators within the probable errors. An essentially calcium matrix is provided by equal mixture of the rock with calcium carbonate. This eliminates variable compositional effects. Though the calcium lines can be used as monitor lines it was found that good precision is available without this operation. The abundance of the reported elements in basaltic rocks are: copper 87 ppm, nickel 134 ppm, chromium 172 ppm. Ni, and Cr are covariant while Cu is independent of the other elements. The covariance of Ni and Cr suggests a common magma source for all basalts since mineralogic effects are not adequate to explain the excellent geochemical coherence observed.

J. VERHOOGEN (University of California, Berkeley, Calif.) *Ionic Ordering and Self-Reversal of Magnetization in Impure Magnetites.* Impure magnetites containing an appropriate amount of aluminum or other elements with an average charge of about three (for example, titanium + magnesium, titanium + vacancies, etc.) may undergo a reversal in their direction of magnetization as a result of an ionic ordering process during and after cooling. Gorter has shown that this phenomenon occurs in the compound Ni Fe Al O_4. Some natural magnetites have compositions which suggest that they may be self-reversing.

GEORGE VERONIS (Institute for Advanced Study, Princeton, N. J.) *The Response of a Stratified Ocean to a Transient Wind Stress.* This study is concerned with the response of a two-layer ocean to transient applied wind stresses. If one considers a spatially periodic wind stress which acts on an infinite ocean for a prescribed period of time, then the periodicity simplifies the mathematics and enables one to draw general conclusions on the response of the two-layer ocean when boundary effects are unimportant. When the time scale of the flow is comparable to lifetimes of storms (of the order of a week), the geostrophic response of the ocean is primarily barotropic for large-scale disturbances and primarily baroclinic for disturbances with spatial scales of the order of 100 km or less. The non-geostrophic oceanic response is baroclinic for all realistic spatial scales. The effect of the variation of the coriolis parameter is such that most of the energy goes into baroclinic motions when the time scale is sufficiently large. The dispersion of energy is studied for the case when the wind blows over a finite portion of the infinite ocean.

E. H. VESTINE (Department of Terrestial Magnetism, Carnegie Institute of Washington, Washington 15, D. C.) *The Aurora Australis and Related Phenomena.* The tentative geographic distribution of the occurrence of aurora in the southern hemisphere, as derived from the results of many expeditions, are described. Comparisons of those results with those for the northern hemisphere are made. Relationships to geomagnetic and ionospheric phenomena are described. Some opportunities afforded by the observing programs of the International Geophysical Year are discussed.

ALLYN C. VINE (Woods Hole Oceanographic Institution, Woods Hole, Mass.), JOHN A. KNAUSS, AND GORDON H. VOLKMANN (Scripps Institution of Oceanography, La Jolla, Calif.) *Transient Currents in the Cayman Sea.* Surface and subsurface current measurements in the eastern Cayman Sea showed a large current flowing against the trade winds for over a week. This current reversed and flowed west at a much slower rate as indicated on current charts. Possible oceanographic and meteorological conditions which might have caused this transient are discussed.

R. B. VICE (U. S. Geological Survey, Washington 25, D. C.) *Methods of Measuring Sediment Yields.* Sediment investigations are designed to describe and explain the properties, origin, and pattern of movement of sediment within and from watersheds. Determination of sediment yields provides quantitative information with which to explain in part the sediment behavior in watersheds. The several methods of determining sediment yields are discussed. Comparisons are made for several methods with respect to scope, cost, and accuracy. The advantages of using the several methods in combination are explored.

GORDON VOLKMANN, JOHN KNAUSS (Scripps Institution of Oceanography, La Jolla, Calif.), AND ALLYN VINE (Woods Hole Oceanographic Institution, Woods Hole, Mass.) *The Use of Parachute Drogues in the Measurement of Subsurface Currents.* A particular drogue technique is discussed. While not new, a few refinements have been added which make this a cheap and comparatively easy method of obtaining a current profile.

BERNARD VONNEGUT (Arthur D. Little, Inc., Cambridge, Mass.) *Role of Clear-Air Conduction Currents to Thunderstorm Electrification Process.* Conduction currents of the order of several amperes are known to flow to thunderstorm clouds. These currents are presently considered to oppose a charge generation mechanism that takes place within the cloud. New mechanisms are suggested according to which these currents intensify rather than oppose the electrification process.

R. C. WANTA (U. S. Weather Bureau, Cincinnati, Ohio) *Application of Extreme-Value Theory to Analysis of Community Air Pollution.* Serial air-pollutant concentrations measured at fixed stations are in many cases distributed approximately logarithmico-normally. This discovery invites study of the distribution of pollutant concentrations from the point of view of more general extreme-value theory. It is shown that concepts familiar in flood-frequency analysis and numerous other fields are applicable in certain cases. An example is given of the use of this approach to an air-pollution record as a diagnostic tool for meteorological analyses.

G. W. WETHERILL, L. T. ALDRICH, AND G. R. TILTON (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) *Comparisons of K-A Ages with Concordant U-Pb Ages of Pegmatites.* Comparisons have been made between K-A ages of mica and concordant uranium-lead ages of uraninite from the same pegmatite. The K-A ages have been

Location	A^{40}/K^{40}	K-A age	U-Pb age
		m y	m y
Spruce Pine, N. C.	0.0213	350 ± 15	375 ± 10
Cardiff Twp., Ontario	0.0729	1000 ± 50	1020 ± 20
Wilberforce, Ontario	0.0695	960 ± 50	1030 ± 30
Keystone, S. Dakota	0.140	1600 ± 80	1600 ± 30
Keystone, S. Dakota	0.119	1430 ± 70	1600 ± 30
Viking Lake, Sask.	0.175	1850 ± 80	1890 ± 40
Bikita, S. Rhodesia	0.300	2550 ± 150	2650 ± 100

calculated using a specific gamma activity of $3.24\gamma/g$ sec and a specific beta activity of $27.6\beta/g$ sec. These data show that consistent K-A ages can be obtained for mica samples using specific activities well within the range of results found by counting measurements.

HARRY WEXLER (U. S. Weather Bureau, Washington 25, D. C.) *Antarctic Research during the International Geophysical Year.* During 1957 and 1958 a dozen nations will maintain 40 geophysical stations in Antarctica. Thus, this Continent, the fifth largest in the world, will be subjected to concentrated, coordinated geophysical exploration to a degree not dreamed possible a few years ago. For the first time, geophysical stations will be established for an extended period of time well away from the coasts, deep in the interior of the Continent. Scientists from the participating nations will cooperate in examining the composition, structure, winds, temperatures, and electrical properties of an atmosphere cut off from sunlight for many months. The thickness of the ice will be surveyed for indications of changes in volume to determine if Antarctic climate is changing. The break-up and movement of the peripheral ice will be studied as a function of wind and ocean currents. The Aurora Australis will be studied and compared with its northern hemisphere counterpart. Intensive measurements will be made of geomagnetism, cosmic rays, airglow, and the ionosphere in an attempt to throw light on the physics of the high atmosphere.

HARRY WEXLER AND M. RUBIN (U. S. Weather Bureau, Washington 25, D. C.) *Antarctic Climatology and Meteorology.* The Antarctic affords an opportunity to investigate a wide range of meteorological problems under conditions not found elsewhere on Earth. These problems include the examination of the thermal, mass, and mobile structure of an atmosphere cut off both from direct solar energy for many months and, in contrast to its Arctic Ocean counterpart, from conduction of appreciable heat from below. The sharp distinction between the troposphere and the stratosphere, so marked elsewhere, is believed to vanish during the polar night over Antarctica.

Another problem is whether the Antarctic troposphere's flow pattern is dominated by the mid-latitude planetary wave system moving like spokes of a wheel around the Pole as appears to be the case in the Arctic, or by waves moving radially outward from the interior of the Continent, as suggested by earlier meteorological observations. A smaller-scale, but important problem, especially for field and aircraft parties, is the drainage, blocking, and deflective influence of mountains and hills on producing local circulations and blizzardy winds up to hurricane force.

The existence of a uniformly thermal and flat snow surface, such as is found for hundreds of miles over the Ross Ice Shelf, will provide an unexcelled natural laboratory to study atmospheric turbulence and energy exchange between atmosphere and snow surface. The incoming and outgoing radiation fluxes, the albedo of the snow surface, the polar white-out, and the variations of ozone and other gases are further examples of problems in polar geophysics which will be investigated during the forthcoming International Geophysical Year.

C. A. WHITTEN (U. S. Coast and Geodetic Survey, Washington 25, D. C.) *Crustal Movements in California and Nevada.* During the past four years a series of geodetic measurements along arcs of triangulation crossing the San Andreas Fault zone has produced results from which a more accurate rate of movement between the oceanic and continental blocks can be determined. This rate is defined in either linear quantities or angular distortion. The uniformity of this angular rate (about one second of arc in the years) of systematic movement, as disclosed by measurements from the Mexican border to Monterey Bay, should prove valuable in further studies of the tectonic stress patterns along the major fault. After the earthquakes of 1954 in the vicinity of Fallon, Nevada, resurveys were made to measure the horizontal and vertical displacements in the Earth's crust which occurred at that time. The results of the horizontal measurements show the typical rebound pattern with differential displacements of about eight feet. The vertical measurements disclose

the dropping and tilting of a valley floor east of the principal fault.

B. L. WIGGIN (U. S. Weather Bureau, Buffalo, N. Y.) *Evolution in Public Weather Service.* An attempt will be made to show the application of communication principles in the evolution of the public weather service for a community of some 2,000,000 having varied interests. The period described is that from 1945 to date.

HARRY B. WILLIAMS (Committee on Disaster Studies, National Academy of Sciences, Washington 25, D. C.) *Disaster Warnings.* Warning is defined as the transmission of messages to individuals, groups, or populations, which provide them with information about (1) the existence of danger, and (2) what can be done to prevent, avoid, or minimize the danger. We shall discuss warnings in terms of (1) initial warnings of future danger, both distant and immediate, (2) warnings after disaster has struck, which are warnings of further danger and are warnings to persons in a different psychological, social, and physical situation, and (3) the effects of pre-disaster warnings upon events in the disaster. The 'wolf-wolf' problem of unfulfilled warnings will be discussed.

Variables affecting the success of warnings will be discussed in terms of (1) the information content of warning messages, (2) the transmission and re-transmission of warning messages through communication channels, both official and unofficial, and (3) the interpretation and evaluation of warning messages by the ultimate recipients. The interpretation and evaluation of warning messages and the actions made in response to them will be discussed in terms of how individuals define their situations. The elements of definitions of threat will be described. A limited number of tentative recommendations will be made for improving the success of warning systems.

MARION B. WOOD (National Bureau of Standards, Boulder, Colo.) *A Study of Magnetic Maps of the Sun.* A study has been made of weak solar magnetic fields using the magnetogram records of H. W. and H. D. Babcock, who very kindly made their records available to us for independent study. Low-latitude, localized magnetic regions of predominantly bipole type or unipole type have been identified as well as the high-latitude polar fields. Only three unipolar regions have been observed, each growing out of antecedent bipolar regions after the characteristic optical activity accompanying the bipolar regions has died out. These unipolar regions have been studied relative to geomagnetic disturbance figure, Ap; no definite identification of the unipolar regions with solar M-regions could be established.

GEORGE P. WOOLLARD (University of Wisconsin, Madison, Wisc.) *Standardization of the World's Gravity Data.* Investigations of the relative accuracy of the world's gravity data show substantial errors in some of the national gravity bases and also the lack of a common reference standard. The need for observations accurate to two milligals and preferably one milligal has led to an international program for the establishment of an acceptable standard which will be discussed along with the applicability of gravity data to geophysical, geologic, and geodetic problems.

Abstracts of the papers presented at the Pacific Southwest Regional Meeting, Los Angeles, California, January 26–27, 1956 listed in the order of the last name of the first author

J. BJERKNES (Dept. of Meteorology, University of California, Los Angeles 24, Calif.) *Meteorological Exploration in Northern Argentina for Hydrological Purposes.* Hydrometeorological exploration in northern Argentina has in recent years been carried on by the New York engineering firm, Parsons, Brinckerhoff, Hall, and Macdonald, under contract with the Argentine government. The writer served as a consultant with the firm during the summer of 1954 and gathered a few results of general interest. The project-region extends from about 3000 to 20,000 ft elevation between 24° and 27°S and receives almost all of its rain with tropical moisture supplies from the northeast. The problem is to devise the best possible year 'round irrigation and hydroelectric use of the water, which mainly falls during the summer from December to March. Indications from the sparse network of rainfall stations make it likely that considerable amounts of convective and orographic rain fall on the steepest part of the escarpment of the Andes. Much less water per unit area comes from the highest mountain slopes because of the reduction of precipitable water with increasing height. Since the dry season is also the cold season, the snow melt does not contribute much to lengthening the season of good runoff. More precise knowledge about the snow budget will be gathered from totalizers installed at about 18,000 ft. Spillway designs on all dams must be ample to take care of floods towards the end of the rainy season when reservoirs are full. Estimates of maximum short-period rates of rainfall can be based only on a few years' records from self-recording gages and from storm transpositions. The maximum rates are similar to those in Panama and considerably less than those in the southern United States. This is mainly due to the complete absence in Panama and South America of tropical cyclones, and their dying remnants over land, which have caused so much flood damage in the United States.

G. A. BROWN, R. F. CLAWSON, AND R. G. THOMAS (State of California, Dept. of Public Works, Division of Water Resources, 1100 S. Grand Ave., Los Angeles, Calif.) *The Relation of Surface Water Quality to Rock Type in California.* Studies of mineral analyses of surface waters in California indicate that waters of calcium bicarbonate type may originate from many of the rock types in areas of high rainfall. Total dissolved solids generally decrease as rainfall increases. Areas of granitic and metamorphic rocks were found to yield water of calcium bicarbonate type. Waters from volcanics are more variable and commonly are magnesium and calcium bicarbonate type. Tertiary marine sediments usually yield calcium and sodium sulphate waters in areas of low precipitation. Cretaceous sediments generally yield calcium bicarbonate water, while Jurassic sediments, metavolcanics, and serpentine yield magnesium bicarbonate water. There are notable variations in the quality of water from sedimentary

environments which may be partially explained by the differences in depositional environment, source materials, and subsequent geologic history. It is believed that these relationships may serve as a guide in evaluation of water quality in areas where rock types are established and water analyses are not available. They may possibly be used as a guide in determining whether water in a given area is of native quality or has been modified.

FRANK B. CLENDENEN AND ELDON H. RINEHART (College of Engineering, University of California, Berkeley 4, Calif.) *Determination of Ground-Water Recharge from Precipitation Deep Percolation.* Ground water has deservedly been receiving increasing attention from water-resource developers during recent years. It is probable that in the western United States groundwater utilization has doubled since 1940. Accompanying such accelerated usage have come the problems of lowering ground-water levels, basin mineralization, sea-water intrusion, and overdraft. These and related problems necessitate careful analysis of ground-water basin characteristics in their solution. A primary source of ground-water replenishment is deep percolation of precipitation that falls directly on valley alluvium. Various means of determining such ground-water accretion are discussed and evaluated from the standpoint of usability in water resources development. In connection with long-range water resources planning for California the problem of determining deep percolation of precipitation was encountered. The method used by the investigators utilized a watershed of about 50 sq mi that was located entirely on alluvium. The measured runoff together with estimated consumptive use and soil-moisture replenishment was subtracted from precipitation on a monthly basis to yield the deep percolation.

PAUL R. DAY (Dept. of Soils and Plant Nutrition, University of California, Berkeley 4, Calif.) *Dispersion of a Moving Salt-Water Boundary Advancing through Saturated Sand.* When salt water displaces fresh water in sand, the boundary between the two liquid phases becomes diffuse after a short period of flow. The dispersion of salt occurs at a much greater rate than can be accounted for by ion diffusion. The effect has been attributed to a mechanism referred to here as hydrodynamic dispersion, a general phenomenon arising from the fact that the velocity of the moving stream varies from point to point in the porous system. The mathematical treatment of the problem is based upon a theory developed by Scheidegger. Equations have been derived for the dispersion of salt water injected in the stream. The theory has been tested by displacing pure water with salt water in a column of saturated sand and determining the concentration of effluent as a function of time. The measured concentrations vary with time as predicted by theory.

WILLIAM R. FERRELL (Los Angeles County Flood Control District, 2250 Alcazar St., Los Angeles, Calif.) *Los Angeles County Flood Control District Initiates a Comprehensive Study of its Debris Problem.* A gradually increasing need has developed for a comprehensive study of the actual and potential debris problems of the Los Angeles County Flood Control District. It has become evident that the construction of debris basins is not a complete solution to the problem of debris control. The removal of debris from debris- and flood-control structures is progressively becoming more expensive because of the increasing number of dams and debris basins, increasing labor and equipment prices, longer hauling distances, and lack of sites for disposal of debris. It is thus necessary, for planning purposes, that a complete appraisal be made of the debris problem.

A Debris Reduction Study Group, a task force which will be responsible for making such a comprehensive study, began operation on July 1, 1955. This Group will make a debris potential appraisal and will study methods of reducing debris movement from watersheds into both unprotected developed areas and into District flood and debris control structures. The results of these studies will form the basis for a District-wide comprehensive debris-reduction plan.

J. D. ISHERWOOD (Engineering Research, University of California, Los Angeles 24, Calif.) *Hydrology of Shallow Ground Waters of the Oxnard Plain, Ventura County, California.* This investigation deals with the hydrology of the shallow 'semiperched' water table. A piezometer network indicated that ground water flows toward the southwest, following the main surface drainage channels. A downward vertical gradient was also apparent over the entire area, indicative of a poorly permeable barrier layer between 16 and 20 ft below the soil surface. The yearly rate of deep percolation was established.

Observations on recession rate of the water table near individual farm tile drains indicated an exponential decline in the ground-water level at the mid-point between drains. For given physical dimensions of soil volume drained by a tile drain this recession rate is proportional to drainable pore space and permeability. A method for computing intermediate drain spacing for any desired rate of mid-point recession, by installation of two widely spaced drains and determination of the recession rate at a point midway between them, is outlined.

CURTIS E. JOHNSON (U. S. Agricultural Research Service, P. O. Box 513, Bakersfield, Calif.) *Utilizing the Decomposition of Organic Residues to Increase Infiltration Rates in Water Spreading.* The infiltration rate varies with the kind, amount, and stage of microbial decomposition of organic materials available or incorporated in a soil. Decomposition periods were studied and counts of microörganisms made. The more readily available organic components of plant residues are decomposed during the initial 30- to 60-day incubation period, after which the more resistant components continue to decompose at a reduced rate. Materials such as redwood sawdust which consist almost entirely of substances highly resistant to decomposition have a rather steady, slow decomposition rate. Nitrogen added as ammonium nitrate stimulates decomposition, the effect depending on the resistance of the material to decomposition and the original carbon-nitrogen ratio. Microörganism counts obtained were generally highest when decomposition rates were high.

Incubation methods are discussed, including length of incubation and continuous leaching versus keeping the soil near field capacity. Infiltration rates obtained on 0.005 acre field test ponds treated with cotton-gin trash, alfalfa hay, and other plant residues are presented. The use of organic residues to increase the infiltration rate of water spreading areas is discussed.

GERALD B. LEVIN (Corps of Engineers, 751 S. Figueroa St., Los Angeles 17, Calif.) *Application of*

Precipitation Forecasts to Reservoir Regulation in the Los Angeles Area. The Los Angeles District, Corps of Engineers, operates nine flood-control dams in the Los Angeles area. In order to achieve maximum flood-control benefits from these structures, they must be operated as efficiently as possible. A prerequisite for efficient operation is the preparation of runoff predictions based upon precipitation forecasts. Although flood-control dams in the Los Angeles District are usually operated in accordance with fixed operation schedules, it may be advisable under certain emergency conditions to deviate from the predetermined plans. When an emergency occurs at a dam, a runoff prediction is prepared. This prediction is used to determine the maximum water-surface elevation that may be expected in the reservoir behind the dam. A decision can then be made regarding the advisability of deviating from the fixed operation schedule.

BEN E. LOFGREN (U. S. Geological Survey, Ground-Water Branch, 2520 Marconi Ave., Sacramento 21, Calif.) *Ground-Water Hydrology of Ogden Valley, Utah.* The unique hydrologic setting of Ogden Valley, in north-central Utah, provides a favorable experimental area for the study of ground-water movement in an isolated artesian aquifer under 'loaded' conditions. Situated as a 'back-valley' within the lofty Wasatch Mountains, this basin is bounded on all sides by mountainous highlands and is drained through a single narrow outlet. Pineview Reservoir, constructed in 1936, inundates the lower sixth of the valley floor; and, by changing the surface loading on an extensive artesian ground-water system, the reservoir affects not only the discharge of a group of flowing wells in operation on the submerged valley floor, but also the natural upward leakage through the artesian confining layer.

Although the permeability of the confining layers is low, the quantity of ground water that leaks through this blanket of sediments is significant. By increasing the stage of Pineview Reservoir 47 ft, water levels in nearby observation wells are raised as much as 30 ft, and the natural leakage from the artesian aquifer is decreased from 21 to about six cfs. During this same loading cycle, the discharge from the submerged flowing wells is increased from 24 to 31 cfs. It is concluded that the increase in well discharge caused by raising the reservoir stage is derived by intercepting water which, under natural conditions, leaks through the confining beds in the vicinity of the wells, and that the increase in head is accompanied by a decrease in underflow from the recharge area.

A. F. PILLSBURY, L. O. WEEKS, J. R. SPENCER, AND R. C. REEVE (Dept. of Irrigation and Soils, University of California, Los Angeles 24, Calif.) *Discharge of Tile Drainage Systems in an Irrigated Desert Area of California.* Good records of discharge of tile drainage systems have been lacking for desert areas. Information on maximum discharge is essential for design. Many measurements have been made in Coachella Valley. From these records the empirical formula $q = 50L^{-0.25}$, where q = maximum discharge in gallons per minute per thousand feet of tile, and L = length of tile in thousands of feet, is obtained. By using the average of 162.5 ft of tile per acre, the above formula can be converted to $Q = 0.028a^{0.75}$, where Q = flow total in cfs and a = area in acres. Reasons are given why these formulas are considered conservative for design purposes. With some variation in constants, it appears probable that the formulas can be applied to other areas.

JOHN REBER (706 Ashbury St., San Francisco 17, Calif.) *The Reber Plan for San Francisco Bay and for Exportation of Water South.* The Reber Plan is really a three-part subject, as it combines (1) a master plan for the San Francisco Bay Metropolitan Region with (2) a state-wide water and transportation project affecting both northern and southern California, and (3) contains basic military necessities for the armed forces and civilian populations.

The planning proposes unifying the San Francisco Bay area by land-linking both the Marin and San Francisco Peninsulas with the mainland of Contra Costa and Alameda Counties respectively with earth-and-rock dams each about four miles long, and each having the dual purposes of water conservation and providing arterials for transporting automobiles, rapid transit, railroads, and military equipment across San Francisco Bay. These two trans-bay dams combined with land-fills along the east bay shore connecting them, and bisected by a ship canal, would transform about ⅓ of the 320,000-acre area of San Francisco Bay into twin fresh-water lakes; and with the lower lake receiving its supply of water from the upper lake via the ship canal. Spillways in the upper dam, ship locks, underpass traffic tubes, and fishways complete the physical works, which, from a water conservation and distribution standpoint, aim first to gain control of, and then to distribute, portions of the runoff of the Golden Gate Drainage Basin of California, which constitutes the fourth largest volume of water flowing to the sea within Continental United States.

With the water problems of the 12 counties of the Bay Region bordering on the twin fresh-water lakes automatically solved, water would be pumped down the west side of the San Joaquin Valley and, via a tunnel through the Tehachapis, to Southern California.

As a tool in resolving hydraulic problems, a scale model of San Francisco Bay and environs is being constructed at the Army Base Laboratory, Sausalito, and will be in operation in the fall of 1956. The survey, estimated to require five years, should be completed by 1960.

OSVALD J. SIBUL AND ERNEST G. TICKNER (Institute of Engineering Research, University of California, Berkeley 4, Calif.) *A Model Study of the Run-Up of Wind-Generated Waves on Levees with Slopes of 1:3 and 1:6.* The run-up, under wind action, of wind-generated waves on levees with slopes of 1:3 and 1:6 was studied in a laboratory wind tunnel. For the lower wind velocities the results indicate the same relative run-up values as found at the Waterways Experiment Station, Vicksburg, Mississippi, where the tests were completed with mechanically-generated uniform waves which were not affected by wind. For higher wind velocities, however, the run-up increases with increasing wind velocity and may reach double the value (above MWL) of run-up where no wind is involved. Run-up on the 1:3 slope was found to be considerably higher than that on the 1:6 slope (by a factor of approximately 2.5), which confirms the trend as found at the Waterways Experiment Station using uniform waves.

L. H. STOLZY, G. A. CRABB, JR., AND A. E. ERICKSON (Dept. of Irrigation and Soils, Citrus Experiment Station, University of California, Riverside, Calif.) *The Use of a Recording Resistance Bridge in Soil-Mois-*

ture Studies. A Leeds and Northrup Micromax was used with plaster-of-Paris and nylon blocks to record soil-moisture changes at the Michigan Hydrologic Research Project. Soil-moisture blocks were buried at different depths in the soil profile under alfalfa, oats, and blue grass. The moisture data were correlated with rainfall and runoff data collected at the Project. An analysis of the data showed the transmission rates to be much greater for the soil profiles under alfalfa and grass than for the soil profile under oats. The infiltration capacity based on rainfall and runoff data also showed the transmission rates under alfalfa to be much greater than the one under oats.

DALE SWARTZENDRUBER AND MARTIN R. HUBERTY (Dept. of Irrigation and Soils, University of California, Los Angeles 24, Calif.) *Use of Infiltration Equation Parameters to Evaluate Infiltration Differences in the Field.* The quantity of water y, which will enter a soil when water is applied to the surface, decreases with time t. Initially the rate of entry dy/dt is high, but decreases steadily, and, depending upon the circumstances, may eventually reach a nearly constant value. This makes it difficult to determine the best infiltration characterization for a given soil condition.

Several infiltration equations have appeared in the literature. One of these is the empirical $y = At^B$, where A and B are constants. In the present investigation, the constants A and B are considered for their usefulness in characterizing infiltration in field basins on Greenfield loamy sand, a deep soil without profile development. The product AB is compared with an arbitrary parameter R_T which is simply the average rate over the first two hours of infiltration. Results indicate that the product parameter AB is useful in the evaluation of infiltration differences, and that it is at least 20 pct more efficient statistically than the arbitrary parameter R_T.

G. S. TAPLEY (City of Los Angeles, Bureau of Engineering, Dept. of Public Works, 200 N. Spring St., Los Angeles, Calif.) *Velocity, Shear, and Drag Distribution for Wide Open Channels.* The discharge in a portion of a wide channel intercepted between a side wall and a water boundary at a distance z from the wall, if shear on that boundary is neglected, is given by Mannings' formula

$$Q = \frac{1.486}{n} S^{1/2} \frac{A^{5/3}}{P^{2/3}} = G \frac{A^{5/3}}{P^{2/3}} \qquad (1)$$

The velocity at the water boundary is then

$$v = \frac{dQ}{y dz} = \frac{Q}{y}\left[\frac{5}{3}\left(\frac{A}{P}\right)^{2/3}\frac{dA}{dz} - \frac{2}{3}\left(\frac{A}{P}\right)^{5/3}\left[\frac{dP}{dz}\right]\right] \qquad (2)$$

and the drag

$$\tau = wS\frac{DA}{DP} \qquad (3)$$

If the channel cross section is such that the depth y decreases as z increases, a point is reached where $R\left(=\frac{A}{P}\right) > y$; beyond this point the side wall has no effect, and the velocity at any value of z is

$$v = Gy^{3/2} = G\left(\frac{dA}{dP}\right)^{3/2} \qquad (4)$$

Experimental results show that velocities obtained by (2) and (4) are approximately correct.

The effect of shear, τ_w, on the water boundary can be included in (1) and (2) if the 'effective' wetted perimeter,

$$\bar{P} = P \pm \tau_w y/\tau \qquad (5)$$

is substituted for P where $\bar{\tau}$ is the average drag. If velocity local distribution is known, $\bar{P}$ and subsequently τw and the effective local drag $\bar{\tau}$ can be determined. A similar process can be applied to (4). It is shown that the effect of the side wall extends only a limited distance from the wall, and that geometrical properties of the cross section determine this distance.

FRED E. TATUM (Corps of Engineers, 751 S. Figueroa St., Los Angeles 17, Calif.) *Transposition of a Standard Project Storm.* The standard project storm, as used by the Corps of Engineers to develop a project design flood, is defined as the most critical storm of record in the region. The most critical storm will vary depending upon size and geographic location of the drainage area. The standard project storm described in this paper is the high-intensity storm most generally used for drainage areas of 50 sq mi or less. The most critical storm for small drainage areas in the Los Angeles area is the storm of March 3–4, 1943. This paper presents the method used in transposing this storm over the project area and in developing the rainfall pattern. Isohyetal maps for each 15-minute period during the three-hour storm were drawn. Area-depth curves were developed from these maps from which the average rainfall time distribution, and precipitation for the project drainage area, can be determined. This eliminates the actual transposing of each 15-minute isohyetal map over the area and gives comparable results.

HAROLD C. TROXELL (U. S. Geological Survey, 429 U. S. Post Office and Court House, Los Angeles 12, Calif.) *Distribution of Natural Water Loss in the Mountains of Southern California.* Observational data obtained at various points in the mountains of Southern California indicate that a considerable part of the basin's precipitation is lost to the atmosphere by evapotranspiration. Occasionally the engineer is called upon to obtain the areal distribution of this basin-wide loss. Currently one of the most promising methods for accomplishing this distribution in Southern California is based on the well-known P/E factor, where P represents the moisture availability and E the opportunity for evapotranspiration. The moisture availability is based on the precipitation and the opportunity for evapotranspiration on the evaporation from a type-A Weather Bureau pan. Where evaporation records are not available, suitable substitute values can often be estimated from regional temperature, humidity, and wind records.

BESSEL D. VAN'T WOUDT (Irrigation Dept., University of California, Davis, Calif.) *Observations on the Efficiency of Sub-Irrigation in Heavy Soils.* The interest in sub-irrigation has lately been revived because of its successful application in a number of sandy soils, peats, and some heavy soils in the Netherlands. In heavy soils the difficulty is encountered that water extraction by roots tends to exceed moisture replenishment from a water table. This is related to the slow capillary movement in heavy soils and to the fact that the rate of this movement declines progressively as the

soil moisture content is further depleted by the roots. The rate may be maintained where the soil is kept moist by occasional rain storms during the period of sub-irrigation. This point is illustrated by experimental work at Rukuhia, New Zealand. Measurement of pasture production at various depths of water table and under varying climatic conditions showed that sub-irrigation can be quite successful if supplemented by rain; in the absence of rain sub-irrigation was quite inefficient. Some observations show that substantial amounts of water can be derived from a water table, even in heavy soils, where active roots penetrate close to it, but an undue rise in the level of the water table should be averted in that case.

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Notes and Personalia

Notes

CORRIGENDUM—In the article by Davidson and Barad in the April, 1956, issue of the *Transactions*, page 170, a fifth term was omitted at the end of the denominator in Eq. (6). This should be $-4 \log z_0$ so that the equation will read

$$R_{ad} = \frac{\log z_4 + \log z_3 - (\log z_2 + \log z_1)}{\log z_4 + \log z_3 + \log z_2 + \log z_1 - 4 \log z_0} \quad (6)$$

GRANTS OF NATIONAL SCIENCE FOUNDATION—The National Science Foundation has recently announced 167 grants totaling over $2,000,000 during the quarter ending March 31, 1956. The grants include tree-ring histories of climatic changes at the University of Arizona (Edmund Schulman), $18,800; radiocarbon dating at the University of Colorado (R. N. Keller), $7,000; radiocarbon dating and other forms of geochronometry at Yale University (E. S. Deevey), $27,200; salinity and current distribution in the St. Marks River estuary at the State University of Florida (F. C. W. Olson), $650; geochemical investigations of sedimentary rocks at the Massachusetts Institute of Technology (William H. Dennen and Ely Mencher), $17,700; research instrumentation for sampling sea water at all depths at the Woods Hole Oceanographic Institution (Vaughan T. Bowen), $3,500.

ASSISTANTSHIPS IN OCEANOGRAPHY AND METEOROLOGY AT TEXAS A AND M COLLEGE—Research Assistantships are available to qualified graduate students in physics, chemistry, geology, meterology, biology, and engineering for 1956–57. They provide for stipends up to $2400 each, and permit the assistants to take standard curricula leading to graduate degrees in oceanography or meteorology. Several $500 scholarships and student assistantships are also available for undergraduates working toward a BS degree in meteorology. It is expected that positions will be filled by August 31, 1956. Further details may be secured from the Department of Oceanography, College Station, Texas.

METEOROLOGICAL BUOY—A meteorological buoy, arranged to serve as a robot marine weather station that can be anchored like a navigational buoy, has been developed by the National Bureau of Standards. This will send weather data from remote areas and can be left unattended for as long as six months. It has a radio range of about 800 miles. The buoy is 20 ft long and ten feet wide with a draft of about three feet and is constructed of aluminum and other nonmagnetic alloys. It has two masts and can be anchored in water as deep as 3600 ft. The four watertight wells contain the meteorological equipment assembled in shockproof units.

TESTS OF NEW RADIO BUOY—A new radio-telemetering buoy has been set out to the south of Martha's Vineyard, Massachusetts, in 30 fathoms of water by the Woods Hole Oceanographic Institution. This instrument was developed by the Institution and will radio surface temperatures of the water twice daily. The temperature is measured by the aid of a thermistor with recordings to 0.4°C. The range of signals is about 100 miles.

NEW MAPS OF THE U. S. GEOLOGICAL SURVEY—The U. S. Geological Survey has announced the publication and release of the following new maps: two-color map of Pennsylvania compiled in cooperation with the State of Pennsylvania on a scale of 1:500,000 on a single sheet 42 by 29 inches, this being available also as a five-color highway and contour edition; topographic map of the State of Kentucky on a scale

of 1:24,000 on sheets 7½ minutes of arc in size (12 other States have complete map coverage, but only three of these are covered by modern mapping); topographic map of Mount Rushmore, South Dakota, quadrangle; four geologic maps of the Michigan copper district; 18 geologic maps covering the Uravan mineral belt in southwestern Colorado; a revised map showing gas and oil fields and dry holes in Montana including the Williston Basin area. Announcement has also been made of a study of the stratigraphy of the outcropping Cretaceous rocks of Georgia.

MEETING ON OCEANOGRAPHY OF THE NORTH PACIFIC—Representatives of the organizations which carried out the cooperative oceanographic survey of the North Pacific, known as NORPAC, met in Honolulu, February 13–17, 1956, to consider the results of the earlier endeavor and to lay plans for further cooperation on oceanographic work in the Pacific. Representatives were on hand from Japan, Canada, New Caledonia, and the United States. A summary of the findings may be secured by writing to Joseph L. Reid, Jr., Scripps Institution of Oceanography, La Jolla, California, who served as Secretary of the group.

RETURN TO SERVICE OF THE KETCH *Caryn*—The *Caryn*, after being laid up for about a year, has recently been on a six-week cruise to the West Indies with L. Valentine Worthington serving as chief scientist. The cruise was planned to obtain more information regarding the deep cold water of the Caribbean which has been warming up and has not been renewed since the end of the Eighteenth Century. This cold water is separated from that of the North Atlantic by sills between the islands, and a thorough survey of the depths of the Windward Passage between Cuba and Haiti over which the deep water is thought to have come from the Atlantic was undertaken.

INSTITUTE FOR SOLAR-TERRESTRIAL RESEARCH—An Institute for Solar-Terrestrial Research has been established at the High Altitude Observatory of the University of Colorado. The research work will be undertaken by the observatory staff and by invited visitors. Initially a four-year program has been set up that will be devoted to the study of the effects of solar activity on weather. A six-week seminar on solar weather research will be held June 18–July 28, 1956.

SUMMER SESSION AT MASSACHUSETTS INSTITUTE OF TECHNOLOGY—The summer session will include a two-week summer program on hydrodynamic stablity and turbulence, July 16–27, 1956, one on orbital and satellite vehicles, August 6–17, and another on tropical hurricanes, August 20–31, 1956. Additional information may be secured by writing to the Office of the Summer Session at M.I.T., Cambridge 39, Mass.

SEVENTH ALASKAN SCIENCE CONFERENCE—The Seventh Alaskan Science Conference will be held in Juneau, Alaska, September 27–30, 1956 and will cover a broad field of the sciences, including various aspects of geophysics. Interested persons should write to Troy L. Pewe, Box 4004, College, Alaska.

RELEASE OF REPORT ON GEOLOGIC STUDIES OF WATER POWER SITES IN ALASKA—The U. S. Geological Survey has recently released to open file a report entitled Geology of Water Power Sites on Crater Lake, Long Lake, and the Speel River near Juneau, Alaska. The report is available for public inspection at the Library of the Survey in Washington, D. C., and at several other locations throughout the country including Juneau, Anchorage, Palmer, and College in Alaska.

IMPROVEMENT IN SIGNAL BROADCAST OF THE NATIONAL BUREAU OF STANDARDS—The Bureau announces improvements in technical radio broadcast services given by WWV near Washington, D. C., and WWVH in Hawaii. Users may now make better assessment of high-precision oscillators and clocks without waiting for correction data. The broadcasts have been increased in accuracy to a part in 100 million, and frequencies are now normally held within plus or minus one part in a billion of NBS primary standard of frequency, with adjustment, if necessary, being made daily at 19h 00m UT.

METEOR STUDY AT HARVARD COLLEGE OBSERVATORY—An extensive program for the study of meteors by radar methods is being undertaken by Harvard College Observatory in cooperation with the Lincoln Laboratory of the Massachusetts Institution of Technology. The work is under the direction of Fred L. Whipple with Gerald S. Hawkins, who has recently arrived from Manchester University, England, as Scientist in Charge.

FALL MEETING OF THE AMERICAN CONGRESS ON SURVEYING AND MAPPING AND THE AMERICAN SOCIETY OF PHOTOGRAMMETRY—The joint fall meeting of these two organizations will be held in Denver, Colorado, September 30–October 2, 1956. For further information write to Box 1407, Edgewater Branch, Denver 14, Colorado.

SCIENCE HOUSE UNDER CONSTRUCTION IN PAKISTAN—The Ismail Science House to house an extensive scientific library and provide a central meeting place for scientists is now under construction at Lahore.

NEW PUBLICATION ON INSTRUMENTS AND METHODS FOR RADIOACTIVITY DETECTION AND EXPLOITATION—A recent issue of *The Quarterly* of the Colorado School of Mines (v. 51, no. 1) includes a section on the theory, development, and applications of radioactivity detection instruments. The second section outlines current techniques of operation and the appendix includes source information on exploration and exploitation.

MEETING ON THE SCIENTIFIC BASIS OF WEATHER MODIFICATION STUDIES—This was held April 10–12, 1956 at the Institute of Atmospheric Physics, University of Arizona. Scientists representing the various cloud-modification and cloud-physics research groups from all over the world were present and took stock of the current position of artificial nucleation techniques.

Through aid of the Rockefeller Foundation, nine scientists from abroad were included. The proceedings of the Conference have been processed in mimeographed form with distribution limited to educational and research institutions. Requests for copies should be addressed to the Institute of Atmospheric Physics, University of Arizona, Tucson 25, Arizona.

SPECIAL DOUBLE NUMBER OF *Geochimica et Cosmochimica Acta*, JULY–AUGUST, 1956—This special number will contain papers entitled Silica in Hot Springs Waters, by Donald E. White, W. W. Brannock, and K. J. Murata; Dissolution and Precipitation of Silica at Low Temperatures, by Konrad B. Krauskopf; and Potassium-Argon Dating, by R. E. Folinsbee. Inquiries should be addressed to the Pergamon Press, Inc., 122 East 55th Street, New York 22, N. Y.

NEW LIST OF PUBLICATIONS OF NEW YORK STATE MUSEUM—This list, which includes a considerable number of items relating to geology and paleontology, is now available without charge by addressing the Museum at Albany 1, N. Y. The stock of some of these items is small, and, because of this, preference in orders will be given to libraries of universities, foundations, and other organizations.

CONFERENCE ON THE UTILIZATION OF FLUID AND SOLID WASTES; BIOLOGICAL AND CHEMICAL PROBLEMS—This Conference will be held in Munich, Germany, by the Bavarian Biological Research Laboratory from October 8 to 12, 1956. Inquiries and applications for admission should be addressed to Prof. H. Liebmann, Bayerische Biologische Versuchsanstalt, Veterinärstrasse 13, München 22, Germany.

NEW COURSE IN GEOMECHANICS—A new course in geomechanics will be taught by the University of Utah, Department of Mining and Geological Engineering, in the spring quarter of 1957, open to graduate students. This will include physical and mechanical property of rocks and the influence of mechanical and chemical defects on rock properties, loading limitations, supports, and design of supports.

ARID ZONE RESEARCH PROJECT IN PERU—The 1300-mile stretch of barren coastal wastes of Peru is now under investigation by a group headed by Mogens Køie of the University of Copenhagen, under the sponsorship of the Arid Zone group of Unesco and the Peruvian Government. They will map the soils to determine which are suitable for development to raise profitable crops, and engage in other edaphological studies.

Personalia

WILLIAM C. ACKERMANN has resigned his position as Head, Watershed Hydrology Section, Agricultural Research Service, to become Chief of the Illinois State Water Survey. In his new position he succeeds A. M. Buswell who retired in 1955.

STANLEY S. BALLARD, Research Physicist at Scripps Institution of Oceanography, has been elected President of the International Commission of Optics, a semi-independent commission of the International Union of Pure and Applied Physics. He will serve for a three-year term. Last summer he was elected for a four-year term to the newly created office of Vice President for Meetings and Local Sections of the Optical Society of America.

DETLEV W. BRONK, President of the Rockefeller Institute for Medical Research and of the National Academy of Sciences, and Chairman of the Board of the National Science Foundation, was recently given the $1000 Priestley Award of Dickinson College.

ERNST CLOOS, Professor of Geology, Johns Hopkins University, has been awarded a Guggenheim Fellowship. He will devote eight months to tectonic studies in Europe.

E. L. DEGOLYER, petroleum geologist and member of the firm DeGolyer and McNaughton, has been appointed a member of the Board of Regents of the Smithsonian Institution.

JOHN D. HESS has opened an office as Consulting Ground-Water Geologist in El Centro, California. He is also Director of the Valley Analytical and Testing Laboratories. He will offer services in the fields of geochemical interpretation of waters and drainage and will be associated with Ellsworth Shaw in matters relating to agricultural waters.

JESSE E. HOBSON has resigned as Director of the Stanford Research Institute to devote a year to recouping his health and in foreign travel.

WALTER L. HUBER, Consulting Engineer at San Francisco, California, has recently been elected Chairman of the Advisory Board on National Parks, Historic Sites, Buildings, and Monuments of the Department of the Interior.

WALTER HEINRICH MUNK, Professor of Geophysics, Scripps Institution of Oceanography, has been elected a member of the National Academy of Sciences.

ALFRED C. REDFIELD, Associate Director of the Woods Hole Oceanographic Institution, has been named the recipient of the Agassiz Medal of the National Academy of Sciences in recognition of his distinguished contributions to oceanography.

FRANCIS A. RICHARDS, Chemical Oceanographer of the Woods Hole Oceanographic Institution, has recently been awarded a Guggenheim Fellowship for a year's study at the University of Oslo of hydrochemical and biochemical cycles in the eastern North Atlantic Ocean. He was likewise recently named to the Advisory Group on Chemistry for the International Geophysical Year.

ALLEN H. SCHOOLEY, Superintendent of the Electronics Division of the Naval Research Laboratory, is on assignment in Brazil, aiding the Brazilian Navy in the establishment of a Naval Research Laboratory. During his year's leave from his duties in Washington, he will participate in the planning of the Laboratory, the procuring of equipment, and setting up the first research projects.

ZDENEK SEKERA, Professor of Meteorology at University of California, in Los Angeles, has been awarded a Guggenheim Fellowship for eight months of study.

ROBERT G. STONE, Chief of the Technical Information and Publications Division of the Air Weather Service in Washington, D. C., has been named recipient of the Award for Outstanding Services of the American Meteorological Society. Specifically, the citation notes "his many years of faithful editorship of the *Bulletin* of the Society and his active participation in its committee and council work."

FRANCIS JOHN TURNER, Professor of Geology, University of California at Berkeley, has been elected a member of the National Academy of Sciences.

JOHN VERHOOGEN, Professor of Geology, University of California at Berkeley, has been elected a member of the National Academy of Sciences.

WALTER SYDNEY ADAMS, former Director of Mount Wilson Observatory, died May 11, 1956, at the age of 79. He was born in Syria. He took his baccalaureate degree from Dartmouth in 1898, his master's degree from the University of Chicago in 1900, studying subsequently at the University of Munich. He received honorary doctorates from Dartmouth College, Pomona College, Columbia University, University of Southern California, University of Chicago, and Princeton University. He began his professional career at Yerkes Observatory in 1901 and continued in service there until 1923, becoming Director in 1913. From 1923 to 1946, he was Director of the Mount Wilson Observatory and subsequent to his retirement had been engaged in research work at the California Institute of Technology. He was a member of many societies and organizations, honorary and scientific. He had been a member of the American Geophysical Union since 1930.

EDWARD A. (TED) COLMAN, Chief of the Division of Watershed Management Research for the California Forest and Range Experiment Station, died March 20, 1956, at the age of 45. He was born in Yokohama, Japan. He took his baccalaureate degree from the University of California in 1932 and his doctorate in 1942. He had been with the Forest Service since his graduation in 1932, working in various regions but returning finally to California. He was the author of a number of technical publications, his most recent large work being a book entitled "Vegetation and Watershed Management," prepared while on leave from his government duties for the Conservation Foundation. He had been a member of AGU since 1938. A memorial fund has been established in his name to aid in the training of young people for research in watershed management. Contributions should be sent to the Chairman of the Committee establishing the fund, Clark H. Gleason (California Forest and Range Experiment Station, P. O. Box 245, Berkeley 1, California).

FRANK MORRIS COWELL, of the Seismograph Service Corporation, died in Tulsa, Oklahoma, October 11, 1955. He was born in Wichita, Kansas, August 22, 1918. He took his baccalaureate degree from the University of Oklahoma in 1941; and after returning from service during the war, he joined the Seismograph Service Corporation, working in the United States, Colombia, and Venezuela. He returned to the United States in 1949, directing a seismic exploration party in western Texas, New Mexico, Canada, and Mexico. He became ill in 1954 while engaged in work in Colombia. He had been a member of AGU since 1950.

C. LELAND HORBERG, Professor of Geology at the University of Chicago, died August 18, 1955, at the age of 45. He was born in Cambridge, Illinois. He took his baccalaureate degree from Augustana College in 1932 and later taught there. He took his doctorate from the University of Chicago in 1938, and for four years taught geology at the University of Illinois, subsequently working with the Illinois State Geological Survey until 1946. He had been with the University of Chicago since 1946 and had served as editor of the *Journal of Geology* since 1953. He had been a member of AGU since 1947.

JOSE GARCIA MONTES, Director of Industry, Cuban Ministry of Agriculture, died in Havana, June 24, 1955, at the age of 63. He was born in Cuba and was educated at the University of Havana, from which he graduated in 1916. He served in various Cuban governmental departments in the early days of his career and in 1938 was appointed Director of Industry of the Ministry of Agriculture of Cuba. Throughout his career he was at the forefront of the engineering development of his country and was chief designing engineer for several important projects there, including extensive developments of the water supply for the city of Havana. He had been a member of AGU since 1941.

GREENLEAF WHITTIER PICKARD, of Newton Centre, Massachusetts, died January 8, 1956, at the age of 78. He was born in Portland, Maine. He attended Harvard in 1895–1896, and Massachusetts Institute of Technology, 1897–1898. Subsequently he entered service with the American Telephone and Telegraph Co., serving as an Electrical Engineer from 1902–1906. In 1907 he became consulting engineer for the Wireless Speciality Apparatus Company, which he served until 1930. Subsequently he served similarly for the Radio Corporation of America and the Yankee Network in Boston. From 1945 to 1949, he was a member of the staff of one of the suburban laboratories of Massachusetts Institute of Technology and in 1949 became affiliated with Pickard and Burns, with which organization he was active until the time of his death. He became a member of AGU in 1930.

MORRIS MILLER SLOTNICK, a geophysicist with the Standard-Vacuum Oil Company of New York, died suddenly at Dallas, Texas, May 8, 1956, at the age of 54. He was born in Zelva, Poland. He took his degrees from Harvard University: baccalaureate in 1922, master's in 1925, and doctorate in 1926, and had a Rogers traveling fellowship from Harvard in 1926–1927, during which period he studied in Hamburg, and was a national research fellow at Princeton, 1927–1928. He served as an instructor at Harvard after he took his baccalaureate degree, while he was working for his doctorate, and in 1929–1930 he took up duties as Assistant Professor at Grinnell College. In 1930, he became a research mathematician in geophysics with the Humble Oil and Refining Company, where he continued until 1954, at which time he became a geophysics consultant at Standard-Vacuum Oil Company. He had been a member of AGU since 1934.

AVAILABLE REPRINTS

In addition to the back numbers of the *Transactions* of AGU still generally available as listed in the *Transactions* of December 1954, Part 2 (directory), pages 129–130, reprints of the material listed below are also available.

Item	Title	Reference	Price	
			1 to 12 copies	13 or more copies
1	Symposium, Interior of the Earth	v. 35, pp. 47–98, 1954	$1.00 each	$0.80 each
2	Origin and Development of the American Geophysical Union, by Jno. A. Fleming	v. 35, 1–46, 1954	0.25 each*	0.15 each
3	Colloquium on Plastic Flow and Deformation within the Earth	v. 32, pp. 497–543, 1951	1.00 each	0.80 each
4	Symposium on Dynamics of Land Erosion	v. 22, pp. 236–320, 1941	1.00 each	**
5	Symposium on Tectonics of the Crust	v. 21, pp. 153–177, 1940	0.75 each	**
6	Symposium on Geophysical Prospecting	v. 20, pp. 241–303, 1939	1.25 each	**
7	Symposium, The Surface and Subsurface Exploration of Continental Borders	v. 19, pp. 781–826, 1938	1.00 each	0.80 each
8	*Transactions* of 1933, Papers of General Assembly	v. 14, pp. 1–40, 1933	0.40 each	**
9	*Transactions* of 1933, Papers of Section of Meteorology	v. 14, pp. 67–108, 1933	0.40 each	**
10	*Transactions* of 1933, Papers of Section of Hydrology	v. 14, pp. 337–521, 1933	1.50 each	**

* A single copy will be supplied without charge to each member applying.
** Very limited number of copies available.

Orders and inquiries should be sent to
AMERICAN GEOPHYSICAL UNION, 1515 Massachusetts Ave., N.W., Washington 5, D. C.

Union, Section, and Committee Activities

Thirty-Seventh Annual Meeting (1956)

Minutes, General Assembly and Section Meetings

Symposium on the Antarctic

This Symposium was arranged and held jointly by the American Geophysical Union with the U. S. National Committee for the International Geophysical Year and the National Science Foundation. The sessions were held in the Auditorium of the National Academy of Sciences, 2101 Constitution Avenue, N. W., Washington, D. C., April 26 and 27, 1956 on the morning, afternoon, and evening of April 26, and on the morning and afternoon of April 27. The total registration for the two-day Symposium was over 400. The program presented much very live material relating to the Antarctic, including some information about Deepfreeze I, just completed, as well as challenging programs with reference to the contemplated work in connection with Deepfreeze II projected for the coming Antarctic summer, and for the interval of the International Geophysical Year 1957–1958. The abstracts of most of the papers presented on the program are included in this issue under the heading of "Reviews and Abstracts." The program presented was as follows:

Thursday, April 26, 1956, 09h 00m (Chairman, Joseph Kaplan)

Scientific Sessions

(1) Joseph Kaplan: Main Aspects of the IGY Program
(2) L. M. Gould: Highlights of Antarctic Exploration
(3) Paul Siple: Antarctic Geography
(4) John Roscoe: Antarctic Photogeography
(5) Finn Ronne: The Weddell Sea Area

Thursday, April 26, 1956, 14h 00m (Chairman, L. M. Gould)

(6) William E. Davies: Antarctic Stratigraphy and Structure
(7) Duncan Stewart: On the Petrology of Antarctica
(8) Maurice Ewing: Some Problems of Antarctic Submarine Geology
(9) Carl R. Eklund: Antarctic Fauna and Some of its Problems
(10) George A. Llano: Botanical Research Essential to a Knowledge of Antarctica

Thursday, April 26, 1956, 20h 00m (Chairman, L. M. Gould)

(11) R. E. Byrd (Rear Admiral, Ret., and Officer in Charge, U. S. Antarctic Program, U.S.N.): U. S. Antarctic Programs
(12) George Dufek (Rear Admiral, and Commanding Officer, Task Force 43, U.S.N.): Operation Deepfreeze I

Friday, April 27, 1956, 09h 00m (Chairman, A. P. Crary)

(13) Harry Wexler, Antarctic Research during the IGY
(14) J. B. Cochran: U. S. Navy Hydrographic Office Contributions to our Knowldege of Antarctica
(15) Harry Wexler and M. Rubin: Antarctic Climatology and Meteorology
(16) Robert P. Sharp: Objectives of Antarctic Glaciological Research

Friday, April 27, 1956, 14h 00m (Chairman, Harry Wexler)

(17) Edward O. Hulbert: Geomagnetic Disturbances
(18) A. H. Shapley: Clues to Ionospheric Conditions in the Southern Auroral Zone
(19) E. H. Vestine: The Aurora Australis and Related Phenomena
(20) J. A. Simpson: Cosmic Radiation Results from the 1954–1955 Antarctic Expedition

Smoker

The Smoker was held in the Ball Room of the National Press Club, National Press Building, Fourteenth and F Streets, N. W., Washington, D. C., on the evening of Monday, April 30, 1956. There were about 350 in attendance. The gathering was entirely informal and served to provide a pleasant opportunity for those in attendance to greet old friends and meet new ones, and to form ever-changing small discussion groups.

Cinemas of Geophysical Interest

This session was held the afternoon of Tuesday, May 1, 1956, in the Lecture Room of the National Academy of Sciences. The following films were presented:

(1) Birth and Development of Volcano Barcena, Mexico
(2) In the Sun's Laboratory
(3) Great Plains Turbulence Field Project
(4) Tidal Currents in Puget Sound—A Model Study
(5) Aqua-lung Diving in Submarine Canyons (spoken commentary by Robert Dill)
(6) Patents and Air Force Research and Development

It is estimated that during the afternoon about 250 were in attendance.

Evening Session

The Evening Session of the Thirty-Seventh Annual Meeting was called to order by President Maurice Ewing at 20h 00m, Tuesday, May 1, 1956, in the Lecture Room of the National Academy of Sciences, 2101 Constitution Avenue, N. W., Washington, D. C. About 125 were in attendance. After appropriate welcoming

remarks, President Ewing introduced Perry Byerly, Professor of Seismology at the University of California in Berkeley, who addressed the group on the subject, "Fifty Years of Seismology." It had been anticipated at this time that the late President James B. Macelwane would give the presidential address. It was especially appropriate that Dr. Byerly, who was Dr. Macelwane's first student, should make this address in his place on a subject very dear to Dr. Macelwane.

Following this, President Ewing called on Walter D. Lambert to present the citation of Weikko A. Heiskanen as the Eighteenth Recipient of the William Bowie Medal.

President Ewing then made the presentation and Dr. Heiskanen responded with appropriate remarks. The proceedings are set forth in the opening pages of this issue.

The Session then adjourned and was followed by an informal social hour with refreshments in the Auditorium of the National Academy of Sciences.

General Assembly: Symposium on the Proposed Redetermination of the Acceleration of Gravity and Business Meeting

The General Assembly was called to order by President Ewing at 14h 00m, Wednesday, May 2, 1956, in the Auditorium of the National Academy of Sciences. About 200 were in attendance. The President turned over the chair to A. G. McNish, who arranged the Symposium on the Proposed Redetermination of the Acceleration of Gravity. After a few introductory remarks by the chair, the Symposium proceeded as follows:

(1) FRANCIS B. SILSBEE: Importance of the Acceleration of Gravity in Determination of Standards
(2) GEORGE P. WOOLLARD: Standardization of the World's Gravity Data
(3) CHESTER H. PAGE: Some Proposals for Redetermining the Acceleration of Gravity
(4) HUGH L. DRYDEN: Comparison of 1906 Potsdam and 1936 National Bureau of Standards Absolute Determination of Gravity

Following the presentation of each paper, opportunity was given for discussion. (The abstracts of the papers are found in Reviews and Abstracts, of this issue of the *Transactions*.)

Following the Symposium, President Ewing resumed the chair and called the Buiness Meeting to order. The minutes of the Thirty-Sixth Annual Meeting [see *Trans.*, v. 36, pp. 549–551, 1955] were approved.

Report of the General Secretary—In the absence of General Secretary Sayre, the Executive Secretary made a summary report, dwelling briefly on membership, finances, meetings, and publications. He announced the total formal registration at the Thirty-Seventh Annual Meeting as 1348. A recapitulation of changes in membership since April 27, 1955, was given as follows:

Membership, April 27, 1955	5070	
New members, April 27, 1955 to April 25, 1956 (including 100 applications in process)	300	5370
Resigned	171	
Dropped	129	
Inactive	6	
Deceased	24	330
Membership as of April 25, 1956		5040

The names of those deceased are listed in the reports of meetings of the Executive Committee, and brief obituaries are carried as news items in the *Transactions*.

Reports of Standing Committees

Meetings—Chairman John N. Adkins reported that the Annual Meeting next spring will be held on May 6–8, 1957, in the week following the National Academy meetings, and that according to the latest information the next General Assembly of the International Union of Geodesy and Geophysics will be held September 4–14, 1957, in Toronto, Canada.

Reports of Special Committees

Resolutions—Chairman E. H. Vestine presented seven resolutions, all of which were unanimously adopted as follows:

(1) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The District of Columbia Chapter of the American Red Cross has provided the use of its Auditorium for the Thirty-Seventh Annual Meeting of the American Geophysical Union, therefore be it

RESOLVED, That the American Geophysical Union express its great appreciation of this cooperation and instructs the General Secretary to express the thanks of the Union to the appropriate official.

(2) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The National Academy of Sciences and the United States Public Buildings Administration have provided the use of meeting rooms and other services for the Thirty-Seventh Annual Meeting of the American Geophysical Union, therefore be it

RESOLVED, That the American Geophysical Union express its great appreciation of this cooperation, extended over many years, and instructs the General Secretary to express the thanks of the Union to the appropriate officials.

(3) RESOLUTION OF THANKS TO THE CARNEGIE INSTITUTION OF WASHINGTON

WHEREAS, The Carnegie Institution of Washington has for many years provided office space for the American Geophysical Union, without which the Union could not adequately function, therefore be it

RESOLVED, That the American Geophysical Union express its deep appreciation of this continued assistance and instructs the General Secretary to express its thanks to the appropriate officers of the Carnegie Institution of Washington.

(4) RESOLUTION ON TIME-SIGNAL SERVICE

WHEREAS, There is a vital need in all seismological work for accurate time service, and

WHEREAS, The time service maintained by the

U. S. Naval Observatory, the Naval Communications Service, and the National Bureau of Standards has been of great use in this work, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation of the valuable scientific cooperation and reiterate its desire for the continuance of this time-signal service, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of the Navy, the Director of Naval Communications, the Superintendent of the Naval Observatory, the Secretary of Commerce, and the Director of the National Bureau of Standards.

(5) RESOLUTION OF THANKS TO THE UNIVERSITY OF CALIFORNIA

WHEREAS, The success of the Pacific Southwest Regional Meeting at Los Angeles, California, on January 26 and 27, 1956, was due in large part to the space and facilities generously provided by the University of California, therefore be it

RESOLVED, That the thanks of the American Geophysical Union be extended to the University of California for the use of their meeting rooms and other facilities, and that the General Secretary be instructed to forward a copy of this resolution to Chancellor Raymond B. Allen.

(6) RESOLUTION ON MAGNETIC OBSERVATORY AT CARACAS, VENEZUELA

WHEREAS, The Director of the National Observatory at Caracas, Venezuela, has under procurement in Germany the complete equipment for a magnetic observatory in the vicinity of Caracas, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation of the value that this observatory will be to the observatory program of the International Geophysical Year and to the regular net of geomagnetic observatories in equatorial regions, and instructs the General Secretary to so inform Dr Edouardo Rohl, Director.

(7) RESOLUTION ON THE LOCATION OF A THRUWAY NEAR LAMONT GEOLOGICAL OBSERVATORY

WHEREAS, The Lamont Geological Observatory, which is one of the foremost seismological stations in the world, would have the usefulness of its ultra-sensitive instruments seriously impaired by traffic on a nearby major highway, and

WHEREAS, Alternate proposed routes for the Thruway connection would carry such traffic outside the zone of interference, therefore be it

RESOLVED, That the American Geophysical Union urge the Thruway Commission to give due consideration to the critical needs of this important scientific station, and that the General Secretary be instructed to forward a copy of this resolution to the Chairman of the New York State Thruway Commission at Albany, New York.

Tellers—In the absence of Chairman Harry S. Ladd, Acting Chairman Kirk Stephenson reported concerning the elections held by mail ballot during March, 1956. The Committee met on April 11, 1956, voted unanimously to count 12 ballots mailed and received late, and tabulated the ballots as follows (the reports of Section elections were presented before the respective Sections, but are combined here for ready reference):

Total number of ballots received		1770
Rejected ballots		
Ballot without identification on outer envelope	1	
Ballots from non-citizens of the United States	12	13
Qualified ballots tabulated		1757

The following officers were elected for the triennium July 1, 1956 to June 30, 1959:

Officers of the Union

President	Maurice Ewing
Vice President	Lloyd V. Berkner
General Secretary	A. Nelson Sayre

Section of Geodesy

President	Milton O. Schmidt
Vice President	Charles Pierce
Secretary	Frank L. Culley

Section of Seismology

Presidnet	Hugo Benioff
Vice President	Leonard M. Murphy
Secretary	James A. Peoples, Jr.

Section of Meteorology

President	Helmut E. Landsberg
Vice President	Thomas F. Malone
Secretary	Woodrow C. Jacobs

Section of Terrestrial Magnetism and Electricity

President	Henry R. Joesting
Vice President	Leroy R. Alldredge
Secretary	R. E. Gebhardt

Section of Oceanography

President	Roger R. Revelle
Vice President	Henry Stommel
Secretary	Donald W. Pritchard

Section of Volcanology, Geochemistry, and Petrology

President	J. Frank Schairer
Vice President	Francis G. Wells
Secretary	L. T. Aldrich[a]

[a] John C. Maxwell, who was elected as Secretary of the Section of Volcanology, Geochemistry, and Petrology, found it necessary to resign, and L. T. Aldrich has been designated in his place.

Section of Hydrology

President	Ray K. Linsley
Vice President	Harry F. Blaney
Secretary	Ralph N. Wilson

Section of Tectonophysics

President	Harry H. Hess
Vice President	Patrick M. Hurley
Secretary	B. F. Howell, Jr.
Executive Committee	Marland P. Billings, and Francis P. Shepard

The proposed amendment to the Statutes modifying the last paragraph of Article 3(a) was adopted, reading as follows:

Members in good standing for a total of 25 years (or 15 years for members joining before January 1, 1946) shall, following retirement from active professional service because of age or disability and upon written notice to the General Secretary, be extended the complete privileges of membership without further payment of dues. The Executive Committee may also extend these privileges to members for extraordinary services to the Union.

The following candidates were elected to the Committee of the North Central Region: Alvin G. Anderson, Edward M. Brooks, C. Robert Elford, Russell G. Mann, Everett V. Richardson, and Tarmo Waara.

In the Pacific Southwest Region, the following were elected to the Committee to represent the Section of Meteorology: Eugene N. Bollay, R. Corday Counts, Jr., and Robert E. Holzer. In the same Region, the following candidates were elected to the Committee to represent the Section of Hydrology: Harlowe M. Stafford, David K. Todd, and Vito A. Vanoni.

Seventy-six ballots for the Pacific Northwest Region were not tabulated but were given to the Executive Secretary for transmittal to David M. Rockwood in Portland, Oregon, as requested by that Region. (The Regional Chairman has reported that the following were elected to the Regional Committee of the Pacific Northwest Region: Franklin I. Badgley, Clifford A. Barnes, Norbert H. Leupold, Fred Natella, Milton S. Sachs, Vail P. Schermerhorn, and Wilbur D. Simons.)

[The Special Committee of Tellers, appointed by President Maurice Ewing upon nomination of the Section officers, was as follows: Harry S. Ladd, Chairman; Gordon G. Lill, Secretary; Geodesy—Norman F. Braaten, Hyman Orlin, and Don C. Ritchie; Seismology—William J. Best and Wilbur I. Duvall; Meteorology—Charles S. Gilman, Conrad Mook, and William C. Spreen; Terrestrial Magnetism and Electricity—W. J. Dempsey, Elizabeth R. King, and Roland G. Henderson; Oceanography—L. P. Disney, Arthur Maxwell, and Richard Vetter; Volcanology, Geochemistry, and Petrology—Jewell Glass and Thomas P. Thayer; Hydrology—Victor A. Koelzer, H. O. Ogrosky, and Walter T. Wilson; Tectonophysics—Joel H. Swartz and Kirk Stephenson; Pacific Southwest Region—James S. Sweet; North Central Region—W. E. Hiatt.]

No reports of other Committees, Sections, or other groups were presented; information relating to these as reported to the Executive Committee is found in the Executive Committee minutes.

Adjournment—The meeting was adjourned at 16h 24m.

A. NELSON SAYRE, General Secretary
WALDO E. SMITH, Executive Secretary

Appendix A—Minutes of the Annual Meeting of 1956, Section of Geodesy, American Geophysical Union

President Hoskinson called the meeting to order in the lecture room of the National Academy of Sciences at 09h 00m on May 2, 1956. There being no objection from the floor, and no corrections received, the President declared the minutes of the 1955 meeting approved as published [*Trans.* **36**, 551, 1955].

N. F. Braaten, member of the Committee of Tellers, announced the election of officers of the Section for the triennium beginning July 1, 1956 (see Tellers' Report above).

The scientific session proceeded with reading of the following papers:

(1) J. L. STEARN[a] and E. J. PARKIN: A Statistical Analysis of Hiran Measurements
(2) W. S. JARDETZKY: Isostasy and Pole Shift
(3) HOWARD E. TATEL: Gravity Measurements in Alaska and the Yukon Territory
(4) C. A. WHITTEN: Crustal Movements in California and Nevada
(5) BERNARD CHOVITZ[a] and IRENE FISCHER: A New Determination of the Figure of the Earth from Arcs
(6) MILTON E. COMPTON: Geodetic Distances with Geodimeters
(7) M. J. S. INNES[a] and A. M. BANCROFT: Recent Gravity Work of the Dominion Observatory, Ottawa, Canada
(8) R. L. G. GILBERT: Some Comments on the Results Obtained with the Cambridge Pendulum Apparatus in North America

[a] denotes speaker

Approximately 140 members and guests were in attendance. The meeting adjourned at 11h 56m.

FRANK L. CULLEY, Secretary

Appendix B—Minutes of the Annual Meeting of 1956, Section of Seismology, American Geophysical Union

The Thirty-Seventh Annual Meeting of the Section of Seismology was held on April 30, 1956 at 09h 10m in the Lecture Room of the National Academy of Sciences. President Heinrich called the meeting to order and the following business was transacted:

The minutes of the 1955 meeting were approved as published [*Trans.* **36**, 552, 1955].

President Heinrich announced that Perry Byerly of the University of California had been appointed to the Commission for Coordination of Seismological Investigations under the IGY program as the United States representative.

The election of the new officers of the Section was announced (see Tellers' Report above).

L. M. Murphy, Chairman of the Resolutions Committee, suggested that the Resolution on Time-Signal Service be repassed in the wording as at the 1955 meeting. It was approved and forwarded to the Union (see Resolution 4 above). Howard Tatel raised a secondary point on a possible means of improving the time-signal service; the suggestion was put in the form of a motion, was approved, and the following statement was forwarded to the Director of the National Bureau of Standards:

The WWV time signals form an integral part of seismic field work such as the crustal investigations performed in Alaska last summer by Dr. Tatel of the Carnegie Institution of Washington. At times, static makes it impossible to hear or record the second signals while the beginning and ending of the tone modulation can still be satisfactorily identified. If the tone modulation could be interrupted more frequently (during the 60th or first second of each minute, for example) it would considerably improve the service under circumstances such as described above.

We respectfully call your attention to this situation and urge that you give the matter due consideration.

A resolution regarding the effect of a proposed thruway route near the Lamont Geological Observatory on the seismic instruments was proposed by Frank Press, was passed by the Section, and was forwarded to the Union (see Resolution 7 above).

A motion by James T. Wilson that the new officers of the Section confer with the officers of the Eastern Section of the Seismological Society of America on a proposal for a joint meeting with them in May of 1957 received approval.

This concluded the business session which was followed immediately by the presentation of the following scientific papers:

(1) JOHN HERSHBERGER: A Comparison of Earthquake Accelerations with Intensity Ratings (10 minutes).

(2) PERRY BYERLY and JOHN DE NOYER: Energy in Earthquakes Computed from Geodetic Observations (15 minutes)

(3) MAURICE EWING and BRUCE HEEZEN: Mid-Atlantic Seismic Belt (15 minutes)

(4) MAURICE EWING and FRANK PRESS: The Long-Period Nature of S Waves (15 minutes)

(5) FRANK PRESS and MAURICE EWING: A Mechanism for G-Wave Propagation (15 minutes)

(6) FRANK PRESS: Crustal Structure Determined by the Phase-Velocity Method (20 minutes)

(7) HOWARD E. TATEL and MERLE A. TUVE: Seismic Crustal Measurements in Alaska (15 minutes)

(8) HOWARD E. TATEL: Seismic Model Experiments (15 minutes)

(9) L. KNOPOFF and A. F. GANGI: The Scattering of Surface Wave Motions by Topographic Irregularities (15 minutes)

(10) W. T. HOLSER and C. J. SCHNEER: Polymorphism in the Earth's Mantle (Seismic discontinuities without chemical change) (5 minutes)

JAMES A. PEOPLES, JR., Secretary

Appendix C—Minutes of the Annual Meeting of 1956, Section of Meteorology, American Geophysical Union

The Thirty-Seventh Annual Meeting of the Section of Meteorology was held April 30–May 4, 1956, in the auditoria of the National Academy of Sciences, General Services Building, the American Red Cross Building, and in the Congressional and Presidential Rooms of the Willard Hotel. All meetings, except the opening business session, were held jointly with the American Meteorological Society.

The business session was called to order at 14h 00m, April 30, 1956, by Secretary W. C. Jacobs. After receiving the report of the Tellers from Charles Gilman (see Tellers' Report above for results of the elections), the meeting was turned over to the President-Elect, Helmut E. Landsberg.

Since no corrections were received, the Chairman declared the minutes of the Thirty-Sixth Annual Meeting of the Section of Meteorology approved as published [*Trans.* **36**, 552, 1955]. The Chairman then appointed a Committee on Resolutions (Earl Droessler, Chairman; Werner A. Braun; William L. Molo).

This concluded the business session. The scientific program as presented follows:

Monday, April 30, 1956, 14h 00m, Auditorium, D. C. Chapter, American Red Cross (Room 4)

Symposium on Atmospheric Electricity

(1) JOHN F. CLARK: The Distribution of Electric Field, Potential, and Space Charge in the Troposphere

(2) ROY W. HENDRICK: Corona Point Discharge and Re-evaluation of Thundercloud Electric Fields

(3) ROSS GUNN: The Hyperelectrification of Raindrops by Atmospheric Electric Fields and the Observed Space-Charge Densities Inside an Active Thunderstorm

(4) BERNARD VONNEGUT: Role of Clear Air Conduction Currents to Thunderstorm Electrification Process

Tuesday, May 1, 1956, 09h 00m, Lecture Room, National Academy of Sciences (Room 2)
(R. J. Williams, Chairman)

Instrumentation

(5) GORDON D. CARTWRIGHT and VAUGHN D. ROCKNEY: Radiosonde Observations Aboard Merchant-Type Vessels (15 minutes)

(6) PAT. J. HARNEY: Aircraft Temperature Measurements with Vortex Thermometers (20 minutes)

(7) G. L. ARNOLD: A Graphical Method of Interpreting Refractive Index Profiles in Terms of Air-to-air Radar Coverage (15 minutes)

(8) JOHN GERGEN: The Black Ball: A Simple Atmospheric Infrared Detector (20 minutes)

(9) ARTHUR ENGELMAN and LAWRENCE COLIN: Meteorological Effects on Propagation (20 minutes)

Utilization of Non-Standard Observations

(10) MYRON G. H. LIGDA: The Utilization of Radar Observations in Weather Analysis (20 minutes)

(11) H. A. LINTNER, D. ATLAS, and R. WEXLER: Characteristics of Severe Storms as Seen by the AN/CPS-9 Radar (20 minutes)

(12) H. T. MANTIS and F. OHNSORG: The Significance of the Intermediate-Scale Motions Observed with a Constant-Altitude Balloon (20 minutes)

Tuesday, May 1, 1956, 14h 00m, Auditorium, General Services Building (Room 3)

Utilization of Non-Standard Observations

(13) G. D. CARTWRIGHT: Utilization of Non-Standard Observations

(14) PAULINE M. AUSTIN: Applications of the Radar as a Meteorological Instrument

(15) LESTER HUBERT: Rocket Observations in Meteorology

(16) W. W. KELLOGG: Suggestions for Measuring the Circulation in Polar Regions in the Upper Atmosphere by Indirect Methods

(17) H. J. MASTENBROOK: Utilization of Transosonde Data

(18) W. J. THALER in collaboration with J. E. MASTERSON: A Rapid High-Altitude Wind Determining System

Wednesday, May 2, 1956, 09h 00m, Auditorium, D. C. Chapter, American Red Cross (Room 4) (William S. Kotsch, Chairman)

Small-Scale Motions

(19) WILLIAM L. DONN, PATRICIA MILIC, and RENÉE M. BRILLIANT: Gravity Waves and the Tropical Sea Breeze (20 minutes)

(20) H. W. HISER: Gulf Stream Effects on Squall Lines as Observed on Radar at Miami (20 minutes)

(21) JEAN T. LEE and JOSEPH G. GALWAY: Preliminary Report of the Relationship between the Jet at the 200-mb Level and Tornado Occurrence (20 minutes)

Semantics of Issuing Weather Forecasts

(22) G. W. BRIER: The Effect of Errors in Estimating Probabilities on the Usefulness of Probability Forecasts (12 minutes)

(23) WOODROW W. DICKEY: The Use of Strictly Defined Terms in Summertime Forecasts (20 minutes)

(24) JOHN SHERROD and H. NEUBERGER: Understanding Forecast Terms—Results of a Survey (15 minutes)

(25) SUMNER BARTON: Confusion Must be Eliminated in Weather Warnings (20 minutes)

(26) B. L. WIGGIN: Evolution in Public Weather Service (15 minutes)

Wednesday, May 2, 1956, 14h 00m, Congressional Room, Willard Hotel (Room 7)

Symposium on Semantics of Issuing Weather Information and Forecasts

(27) L. P. ALLEN: Semantics and Communications

(28) ERNEST J. CHRISTIE: Some Problems of Practical Meteorology

(29) E. T. HARDING: Weather Information and Forecasts in a Fleet Operation

(30) T. F. MALONE: The Role of Probability in the Communication of Weather Information

(31) H. B. WILLIAMS: Disaster Warnings

Thursday, May 3, 1956, 09h 00m, Caucus Room, Willard Hotel (G. W. Platzman, Chairman)

Dynamics of Large-Scale Motions

(32) ROBERT G. FLEAGLE: On the Dynamics of the General Circulation (20 minutes)

(33) PHILIP D. THOMPSON: A Heuristic Theory of Large-Scale Turbulence and Long-Period Velocity Variations in Barotropic Flow (25 minutes)

(34) MARIANO A. ESTOQUE: A Prediction Model for Graphical Integration (30 minutes)

(35) HERBERT RIEHL and DAVE FULTZ: Structure of Jet Stream and Long Waves in a Dishpan Experiment (30 minutes)

(36) SVERRE PETTERSSEN: Report on an Experiment in Construction of Prognostic Charts (40 minutes)

Thursday, May 3, 1956, 09h 00m, Congressional Room, Willard Hotel (Room 7) (G. P. Cressman, Chairman)

Condensation and Precipitation

(37) MILTON DRAGINIS: New Measurements of Liquid Water in Convective Clouds (15 minutes)

(38) ALBERT MILLER and HANS A. PANOFSKY: Large-Scale Vertical Velocities and Weather, January 1953 (20 minutes)

Data Processing

(39) STUART G. BIGLER: The Use of Television for Local Dissemination of Radar Observations to the Public (15 minutes)

(40) M. L. GREENOUGH and JULIUS F. BOSEN: FOSDIC—A New Approach to Storage and Utilization of Digital Records (20 minutes)

(41) J. LEITH HOLLOWAY, JR.: Smoothing, Filtering, and Inverse Smoothing of Time Series (20 minutes)

(42) ROBERT F. MYERS and DAVID G. RHOADES: Telemeteorology (20 minutes)

(43) IVAN W. BRUNK: Automatic Distribution of Weather Information and Forecasts (15 minutes)

Thursday, May 3, 1956, 14h 00m, Congressional Room, Willard Hotel (Room 7)

Symposium on Data Processing

(44) H. E. LANDSBERG: The Data-Processing Problem in Meteorology

(45) H. A. BEDIENT in collaboration with G. P. CRESSMAN: Automatic Data Processing for Numerical Weather Prediction

(46) BRUCE GILCHRIST: Error-Free Data for Numerical Weather Prediction

(47) FERGUSON HALL: The Spectrum of Data Processing

(48) VINCENT E. LALLY in collaboration with R. F. MYERS and D. H. MCINNIS: Information Content of Weather Charts

Friday, May 4, 1956, 09h 00m, Congressional Room, Willard Hotel (Room 7) (H. W. Ellsaesser, Chairman)

Synoptic Meteorology

(49) DOROTHY L. BRADBURY: An Experiment in Moisture and Stability Analysis (20 minutes)

(50) J. B. Holleyman and Roy H. Blackmer, Jr.: A Meso-Analysis of a Well-Defined Cold Front on September 21, 1947 (20 minutes)

(51) A. K. Showalter: Stability and Thickness Relationships of Two Adjacent Layers (20 minutes)

Hurricanes

(52) William H. Haggard and Hugh S. White: Some Aspects of Hurricane Climatology (20 minutes)

(53) Vaughn D. Rockney: Radar Observation of Middle East Coast Hurricanes (25 minutes)

(54) Erik H. Palmen and Herbert Riehl: On the Balance of Absolute Angular Momentum in Tropical Storms (20 minutes)

(55) Robert A. Hoover: The Characteristics of Hurricanes Associated with Rapid Rises in Sea Level (20 minutes)

Friday, May 4, 1956, 09h 00m, Caucus Room, Willard Hotel (M. L. Barad, Chairman)

Micrometeorology and Pollution

(56) Richard C. Hubley: Turbulent Transfer of Energy Over an Isothermal, Melting Show (20 minutes)

(57) Wayne L. Decker: Estimation of Soil Temperatures from Meteorological Conditions (20 minutes)

(58) Irving A. Singer and Robert M. Brown: The Annual Soil-Temperature Wave at Brookhaven National Laboratory (20 minutes)

(59) A. L. Danis: The Growing Problem of Air Pollution in Florida (15 minutes)

(60) B. Davidson, J. Halitsky, and I. Karmin: A Micrometeorological Survey of the Hudson River Valley Near Buchanan, N. Y. (20 minutes)

Friday, May 4, 1956, 14h 00m, Congressional Room, Willard Hotel (Room 7)

Symposium on Pollution

(61) E. W. Hewson: Atmospheric Pollution by Aeroallergens

(62) F. N. Frenkiel: Radioactive Pollution and Civil Defense

(63) L. Machta: The Application of Gummed Films for the Collection of Settled Particulates

(64) M. Neiburger: Wind Trajectory Studies of the Movement of Polluted Air in the Los Angeles Basin

(65) R. C. Wanta: Application of Extreme-Value Theory to Analysis of Community Air Pollution (20 minutes)

In addition to the above program, the Joint Committee on the Interaction of the Sea and the Atmosphere arranged a program which is reported below in Appendix E, in connection with the minutes of the Section of Oceanography.

Woodrow C. Jacobs, Secretary

Appendix D—Minutes of the Annual Meeting of 1956, Section of Terrestrial Magnetism and Electricity, American Geophysical Union

The Thirty-Seventh Annual Meeting of the Section of Terrestrial Magnetism and Electricity was called to order by President Victor Vacquier at 09h 05m on April 30, 1956, in the Auditorium of the National Academy of Sciences. There were approximately 45 members and guests in attendance. Since no corrections had been received, the minutes of the 1955 meeting were assumed correct as published [*Trans.* **36**, 554, 1955].

President Vacquier announced the results of the recent election of officers (see Tellers' Report above).

President Vacquier pointed out that only three responses had been received to the notice in the December *Transactions* regarding a possible change in name for the Section. He then called for a show of hands to determine the preference among three names with the following results: nine favored the name "Section of Geomagnetism and Upper Atmosphere," no one voted to keep the present name, and six favored the name "Section of Geomagnetism and Aeronomy," which is the name of the corresponding International Association.

After routine announcements the scientific program listed below was presented.

(1) James H. Kraakevik: Conductivity and Conduction Current Density in the Troposphere (20 minutes)

(2) John F. Clark and James H. Kraakevik: Airborne Atmospheric-Electric Studies of Radioactive Contamination (15 minutes)

(3) Victor F. Hess and A. W. Manning: A Study of the Ionization Produced in Various Gases by Cosmic Radiation (15 minutes)

(4) C. Y. Johnson and J. P. Heppner: Positive and Negative Ion Composition of the E-Region from Rocket-Borne Mass Spectrometer Measurements (15 minutes)

(5) M. J. Koomen, R. Scolnik, and R. Tousey: Night Airglow Emission Layers Observed from a Rocket (15 minutes)

(6) Marion B. Wood: A Study of Magnetic Maps of the Sun (10 minutes)

(7) Elwood Maple: Geomagnetic Fluctuations at Frequencies of 3 to 45 c/s at Point Barrow, Alaska (15 minutes)

All papers were presented by the first-named author except for papers (3) and (5) which were presented by the last-named. The session adjourned at 11h 37m.

The second session was called to order by President Victor Vacquier at 09h 05m on May 1, in the Auditorium of the General Services Building. The following papers were presented:

(8) H. Freeborn Johnston: Late Annual Values at World Geomagnetic Observatories (10 minutes)

(9) Edwin J. Chernosky: The Delta Measure of Geomagnetic Activity (15 minutes)

(10) Walter M. Elsasser: Convection in the Core (15 minutes)

(11) J. Verhoogen: Ionic Ordering and Self-

Reversal of Magnetization in Impure Magnetites (15 minutes)

(12) ROBERT E. GEBHARDT: Progress Report on the Fredericksburg Magnetic Observatory (15 minutes)

(13) MAURICE J. DAVIDSON and EDWARD TITUS MILLER: An Airborne Magnetic Survey of the West Indies, Gulf of Mexico, and the Eastern United States Continental Margin (20 minutes)

(14) J. P. HEPPNER: Forthcoming Geomagnetic Studies from Rocket Vehicles (15 minutes)

(15) F. S. SINGER: A New Model of Magnetic Storms and Aurorae (15 minutes)

(16) J. A. JACOBS and T. OBAYASHI: The Sudden Commencements of Magnetic Storms (15 minutes)

After paper number (8) was presented, a resolution submitted by H. Freeborn Johnston was passed by the Section, and forwarded to the Union for further action (see Resolution 6, above).

The meeting was adjourned at 12h 30m.

L. R. ALLDREDGE, Secretary

Appendix E—Minutes of the Annual Meeting of 1956, Section of Oceanography, American Geophysical Union

The meeting was called to order at 09h 15m, April 30, 1956, in the Auditorium of the American Red Cross by President Richard Fleming.

Richard Vetter read a report from the Committee of Tellers giving the results of the election (see Tellers' Report above).

President Fleming noted that the next meeting of IUGG will be in Toronto in 1957. He suggested that, because of confusion that resulted at the Rome meeting concerning the voting privileges of delegates, a chairman be designated by the Section of Oceanography of AGU and be authorized to vote or to name an alternate with authority to vote.

President Fleming also noted that at international meetings it is customary to submit a report concerning the activities of the national organizations represented. He suggested that at the 1957 meeting of the Section of Oceanography of AGU the various oceanographic institutions in the country present reports of their activities and that these reports be made the basis for the American report on oceanography at the 1957 IUGG meeting. He further suggested that the American report to the international meeting be published in the *Transactions* of AGU.

John Lyman noted that the problems connected with the publication of such reports in the *Transactions* were to be studied by a committee, but that no committee had been appointed.

Your Acting Secretary interprets these comments to require action by the Section of Oceanography on two items, they are: (1) The designation of a chairman of delegates to IUGG empowered to name a voting alternate. (2) Appointment of a committee to study the problems connected with the publication of American reports made at international meetings in the *Transactions*.

The Business Meeting was then adjourned and was followed by the scientific sessions which included two general sessions and two sessions held jointly with the Section of Meteorology and arranged by the Joint Committee on Interaction of the Sea and Atmosphere, as follows:

(1) JOHN J. SCHULE: Comparison of Sea Ice Conditions in the American Arctic

(2) BRUNO J. GILETTI and J. LAURENCE KULP: Application of Tritium Measurements to Oceanography and Meteorology

(3) WALLACE S. BROECKER: C^{14} Dating of the Wisconsin-Recent Climatic Change from Ocean Floor Sediments

(4) LANSING P. WAGNER: Hydrography of the Cay Sal Bank Region (Read by title)

(5) G. L. PICKARD and R. W. TRITES: Heat Budget Study for British Columbia Inlets

(6) R. H. FLEMING: Circulation and Water Masses of the Gulf of Alaska (Read by title)

(7) TOWNSEND CROMWELL: Pycnoclines Created by Vertical Mixing

(8) JOHN C. FREEMAN, JR., and LEDOLPH BAER: The Method of Wave Derivatives

Monday, April 30, 1956, 14h 00m, Auditorium, National Academy of Sciences (Room 1)

(9) WILLIAM L. DONN: On the Prediction of Storm Tides Generated by Northeast Storms

(10) JOHN C. FREEMAN, JR., and LEDOLPH BAER: Graphical Computation of Hurricane Storm Tides

(11) WILLIAM L. DONN and MAURICE EWING: Storm Surges and Edge Waves in Lake Michigan

(12) D. LEE HARRIS and ARTHUR PORE: Case Studies of Recent Storm Surges

(13) JOHN G. HOUSLEY and DONALD C. TAYLOR: Application of the Solitary Wave Theory to Shoaling Oscillatory Waves

(14) PETER S. EAGLESON: Properties of Shoaling Waves by Theory and Experiment

(15) FRANK CHEW: A Study of Transverse Motion in the Florida Current

(16) GORDON VOLKMAN, JOHN KNAUSS, and ALLYN VINE: The Use of Parachute Drogues in the Measurement of Subsurface Currents

SECTIONS OF METEOROLOGY AND OCEANOGRAPHY

(Jointly with the American Meteorological Society)

Tuesday, May 1, 1956, 09h 00m, Auditorium, National Academy of Sciences (Room 1) (Charles C. Bates, Chairman)

A New Look at Ocean Currents with Special Emphasis on Transients

(1) D. LEE HARRIS: The Storm-Surge Problem in the United States (20 minutes)

(2) DAL F. LEIPPER: Sea Temperature, Statistics, and Shallow-Water Tidal Currents (25 minutes)

(3) GERHARD NEUMANN: On the Mutual Adjustment of the Horizontal Field of Mass, the

Sea-Surface Topography, and the Level of No Motion in the Gulf Stream (25 minutes)

(4) HUGO MANDELBAUM: Evidence for a Critical Wind Velocity for Air-Sea Boundary Processes (15 minutes)

(5) ROBERT G. FLEAGLE: Comments on the Effect of Air-Sea Temperature Difference on Wave Generation (20 minutes)

(6) JOHN A. KNAUSS: Some GEK Observations of the Equatorial Countercurrent in the Eastern Pacific (25 minutes)

(7) JOHN ROPEK: Towing and Erection of Texas Towers on Georges Bank (color film; 20 minutes)

Wednesday, May 2, 1956, 09h 00m, Auditorium, National Academy of Sciences (Room 1) (Dale F. Leipper, Chairman)

(8) GEORGE VERONIS: The Response of a Stratified Ocean to a Transient Wind Stress (20 minutes)

(9) IRENE BROWNE and A. P. CRARY: Arctic Ice-Pack-Movement Studies (25 minutes)

(10) ALLYN C. VINE, JOHN A. KNAUSS, and GORDON H. VOLKMANN: Transient Currents in the Cayman Sea (25 minutes)

(11) T. S. AUSTIN, E. D. STROUP, and M. O. RINKEL: Variations in the Equatorial Countercurrent in the Central Pacific (25 minutes)

Following completion of the second joint technical session, an open meeting of the Committee was called by Chairman Charles C. Bates, with members Dale F. Leipper and Willard Pierson attending, and members Robert G. Fleagle, Walter Munk, and Alfred Woodcock absent. Discussion touched upon the German meeting scheduled for September, 1956, concerning interaction of the sea and atmosphere, increased availability of platforms such as Texas Towers, radar picket ships, and radio-monitored drift buoys for measuring oceanic conditions, and the current status of the American Meteorological Society's monograph, "Meteorologically Induced Changes in Sea Level." A number of suggestions, particularly with regard to the need for a session on sea-ice forecasting, were received from the floor when topics were requested for the IUGG session scheduled for Toronto in 1957. Other discussants from the floor suggested that the Committee might arrange future symposia on chemical or water exchanges between the sea and atmosphere, particularly in transitional zones, rather than stress sessions that were primarily a mechanism for giving progress reports in already active fields. A joint meeting with an applied group such as fishery biologists was suggested as one possible dynamic approach for the Committee's efforts. The meeting adjourned at 11h 50m.

DAYTON E. CARRITT, Secretary

Appendix F—Minutes of the Annual Meeting of 1956, Section of Volcanology, Geochemistry, and Petrology, American Geophysical Union

President Foshag called the meeting to order at 14h 00m, May 2, 1956. No corrections having been received, the minutes of the Annual Meeting of 1955 were approved as published [*Trans.*, **36**, 557, 1955]. T. Thayer announced the results of the recent election. (See Tellers' Report above.)

The first technical session began at 14h 10m. The program sponsored solely by our Section was as follows:

(1) G. W. WETHERILL[a], L. T. ALDRICH, and G. R. TILTON: Comparisons of K-A Ages with Concordant U-Pb Ages of Pegmatites

(2) L. T. ALDRICH[a], G. W. WETHERILL, G. R. TILTON, and G. L. DAVIS: Comparisons of Rb-Sr Ages with Concordant U-Pb Ages of Pegmatites

(3) PAUL E. DAMON[a], LEON E. LONG, and DONALD R. CARR: Excess Helium and Argon in Minerals

(4) GEORGE R. TILTON[a] and CLAIRE C. PATTERSON: The Isotopic Composition of Lead in Ultramafic Rocks

(5) J. E. HOGG: The Determination of Uranium Mineral Ages by the Lead 210 Method

(6) P. K. KURODA[a] and B. L. ROBINSON: Natural Uranium Chain Reaction and the Uranium-Lead Age of Minerals

(7) WALTER R. ECKELMANN and DONALD S. MILLER[a]: New Uranium-Lead Age Determinations

(8) L. F. HERZOG, W. H. PINSON, JR., and R. F. CORMIER[a]: Sediment Age Determination by Rb-Sr Analysis of Glauconite

Wednesday, May 2, 1956, 09h 00m, Auditorium, General Services Bldg. (Rm. 3)

(9) PATRICK M. HURLEY[a] and WILLIAM H. PINSON, JR.: Variations in Radioactive Elements between Mafic Rock Provinces

(10) HAROLD W. FAIRBAIRN[a] and PATRICK M. HURLEY: Radiation Damage in Zircon from Eastern Massachusetts and Nova Scotia

(11) J. LAWRENCE KULP and WAYNE U. AULT[a]: Sulfur Isotope Variations in Hydrothermal Sulfides

(12) H. P. EUGSTER: Synthesis and Phase Relations of the Biotites

(13) G. KULLERUD[a] and H. S. YODER: Upper Stability Curve of Pyrite

(14) W. C. KRUMBEIN and H. A. SLACK[a]: The Relative Efficiency of Sampling Designs for Sedimentary Particle Populations

(15) D. W. HOOD[a], ELIZABETH RONA, and L. K. AKERS: Determination of Manganese in Sea Water

(16) KARL K. TUREKIAN: The abundance of Cu, Ni, Co, and Cr in Basaltic Rocks

[a] Denotes speaker.

In addition, our Section served as cosponsor of the scientific program of the Section of Tectonophysics.

There was extended discussion of many of the papers but the amount of discussion seemed to vary inversely with the size of the audience. Considerable shuffling in and out of the hall between papers is probably

unavoidable, but the amount of it this year was excessive, distracting the speakers and making it virtually impossible for those near the back of the lecture room to hear the discussion. The parallel scheduling of an excellent motion picture on volcanism greatly reduced attendance at the first session; a number of members complained to the Secretary about this.

FELIX CHAYES, Secretary

Appendix G—Minutes of the Annual Meeting of 1956, Section of Hydrology, American Geophysical Union

President Harold G. Wilm called the Business Meeting to order at 09h 10m, April 30, 1956, in the Auditorium, General Services Building, The President announced the results of the election (see Tellers' Report above).

Vice-President Ray K. Linsley, Chairman of the Committee on Awards, announced that after considerable deliberation the paper "An Investigation of the Freezing of Water in Capillaries" by Charles L. Hosler and C. Robert Hosler (February 1955) had been selected as the best Hydrology paper to appear in the 1955 AGU Transactions, and is to receive the Horton Award for that year. The paper "Capillary Losses from Ground Water" by Irwin Remson and G. S. Fox (April 1955) was selected as the "best first paper" for the year 1955. The paper by William A. Hadley and Raymond Eisenstadt "Thermally Actuated Moisture Migration in Granular Media," (August 1955) was a close second for the Horton Award and definitely deserved Honorable Mention. Certificates of Awards for the first two papers mentioned will be prepared and forwarded to the authors at an early date.

President Wilm announced that the International Association of Hydrology, IUGG, is sponsoring a symposium to be held in Dijon, France, in September 1956 to commemorate the 100th anniversary of the fundamental studies of Darcy. The symposium will cover the hydrology of floods and the study of groundwater phenomena as related to the Darcy law. Program Chairman Ralph N. Wilson reported on the status of the United States papers proposed for the symposium and stated that final selection of papers would be made in the near future.

A brief report on the IUGG meeting scheduled for September 1957 in Toronto, Canada, was presented by President Wilm.

The Business Meeting then adjourned and was followed immediately by the Scientific Sessions, which included two general sessions and two sessions of a Symposium on Watershed Erosion and Sediment Yields. The first scientific session, under the chairmanship of President Wilm, began at 09h 30m, and was presented as follows:

(1) ROBERT T. BEAUMONT: A Criterion for Selection of Length of Record for a Moving Arithmetic Mean for Hydrologic Data
(2) HARRY F. BLANEY: Evaporation Study of Silver Lake in the Mojave Desert (in view of Mr. Blaney's confinement in a Washington, D. C., hospital with a broken ankle, this paper was presented by Dr. Wilm).
(3) G. H. BOLT and R. D. MILLER*: Calculation of Total and Component Potentials of Water in Soil
(4) M. N. E. RIFAI, W. J. KAUFMAN, and D. K. TODD*: Dispersion Phenomena in Laminar Flow Through Porous Media
(5) A. E. SCHEIDEGGER: Correlation Tensors in Statistical Hydrodynamics in Porous Media

The second session, under the chairmanship of Vice President Linsley, began at 14h 00m on April 30, 1956, in the Auditorium, General Services Building.

(6) JOHN C. COOK: Some Observations in a Northwest Greenland Crevasse
(7) JOHN C. COOK: An Electrical Crevasse Detector
(8) LLOYD L. HARROLD: Yield of Water from Small Agricultural Watersheds
(9) F. A. HUFF* and J. C. NEILL: Distribution of Point and Areal Rainfall Rates
(10) M. C. BOYER: A Correlation of the Characteristics of Great Storms
(11) RICHARD D. TARBLE: Precipitation Patterns by Radar Scope Observations
(12) MAX C. BREWER: The Thermal Regime in Arctic Lakes
(13) A. S. ROGERS* and J. H. FETH: Radon Surveys Applied to a Specific Hydrologic Problem

President Wilm introduced Louis C. Gottschalk, Chairman of the Research Committee on Land Erosion, as the Chairman of the opening session of the Symposium on Watershed Erosion and Sediment Yields. This session began at 14h 00m on May 1, 1956 in the Auditorium, District of Columbia Chapter of the American Red Cross.

(14) L. C. GOTTSCHALK: Problems of Predicting Sediment Yields from Watersheds
(15) D. D. SMITH* and W. WISCHMEIER: Sheet Erosion
(16) L. B. LEOPOLD* and M. G. WOLMAN: Stream Channel Erosion
(17) JAMES C. BRICE: Erosion by Terracettes on Loess-Mantled Slopes
(18) PAUL C. BENEDICT: Fluvial Transportation of Sediment

The second session of the Symposium, under the Chairmanship of Paul C. Benedict, began May 1, 1956, at 14h 10m in the Auditorium, District of Columbia Chapter of the American Red Cross.

(19) LOUIS M. GLYMPH: Importance of Sheet Erosion as a Source of Sediment
(20) ALBERT E. COLDWELL: Importance of Channel Erosion as a Source of Sediment
(21) ARTHUR N. STRAHLER: Quantitative Analysis of Watershed Geomorphology
(22) HENRY W. ANDERSON: Relating Sediment Yield to Watershed Variables
(23) WILLIAM C. ACKERMANN: Needed Research in Sedimentation.

* Denotes speaker.

The session adjourned at 16h 40m with closing remarks by President Wilm. Attendance at all sessions was excellent and there was lively discussion of many of the papers.

RALPH N. WILSON, Acting Secretary

Appendix H—Minutes of the Annual Meeting of 1956, Section of Tectonophysics, American Geophysical Union

The business session was called to order at 14h 00m, Monday, April 30, 1956, in the Lecture Room, National Academy of Sciences Building, by President Birch. The minutes of the 1955 meeting were approved as published [*Trans.*, **36**, 559–560, 1955]. The report of the Tellers for the election of officers for the next triennium was given (see Tellers' Report above).

There being no further business a joint scientific session with the Section of Volcanology, Geochemistry, and Petrology followed immediately. The following papers were presented:

(1) RHODES W. FAIRBRIDGE: The Geotectonic Position of Antarctica
(2) W. T. HOLSER and C. J. SCHNEER: Polymorphism in the Earth's Mantle
(3) G. D. GARLAND: Investigations of Gravity and Isostasy in the Southern Canadian Cordillera (20 minutes)
(4) H. S. HEAPS: The Effect of Elastic Intrusions Upon a Gravitational Stress (15 minutes)
(5) C. HEWITT DIX: Part of the Mechanism of Horizontal Shear Faulting
(6) J. H. SWARTZ: Changes in the Absolute Value of the Earth's Magnetic Field at Kilauea Volcano, Hawaii, between 1952 and 1954
(7) D. W. ALLAN and J. A. JACOBS: Initial Thermal Conditions in the Solar System
(8) ROBERT L. MILLER: Speculation on Water Currents in a Black Shale Environment by Use of Orientation and Dispersion of Fossil Fragments
(9) M. J. S. INNES: Gravity and Isostasy in Central Quebec

JAMES T. WILSON, Secretary

Special Announcements

NEW ADDRESS FOR THE AGU—As it is noted in the April issue, the American Geophysical Union plans to move to the new building of the American Association for the Advancement of Science at 1515 Massachusetts Avenue in the latter part of June, 1956. The new address will be 1515 Massachusetts Avenue, N.W., Washington 5, D. C.

THIRTY-EIGHTH ANNUAL MEETING TO BE HELD MAY 6–8, 1957—The Thirty-Eighth Annual Meeting will be held in Washington, D. C., May 6–8, 1957, Monday through Wednesday. This is the first call for titles and abstracts of papers and for suggestions for symposia and other matters relating to the Meeting. Address your communications to the office of AGU or to the appropriate Section Secretary. Watch Special Announcements in subsequent issues for further information.

RESULTS OF ELECTIONS—The results of the elections for officers for the triennium ending June 30, 1959 and the amendment to the Statutes will be found in this issue on pages 384–385. The report also includes an announcement of the results of the regional elections in the Pacific Southwest Region, the Pacific Northwest Region and in the North Central Region.

MEETING OF THE ASSOCIATION OF HYDROLOGY, IUGG, AT DIJON, FRANCE, IN SEPTEMBER, 1956—As noted in the April issue of the *Transactions*, the International Association of Hydrology is planning two symposia to be held at Dijon, France, September 20–26, 1956. Following the meetings, a tour of the Durance Valley in France is contemplated, noting especially hydrologic features relating to ground water, glaciation, and the effect of reservoir storage. Ralph N. Wilson (3322 Stanford Drive, University Hills, West Hyattsville, Maryland) is Chairman of a committee working out arrangements for the United States' participation in this meeting, but in other regards persons should write to the Secretary of the Association, L. J. Tison, rue des Ronces, 61, Gentbrugge, Belgium. The occasion is the commemoration of the centennial of the fundamental work by Darcy.

PACIFIC NORTHWEST REGIONAL MEETING—This meeting will be held in the Seattle-Tacoma area in November, 1956, with the exact dates yet to be set. Clifford A. Barnes (Oceanographic Laboratories, University of Washington, Seattle 5, Washington) has been named Chairman of the Committee on Arrangements. Plans will be made jointly with the Program Committee, with Robert T. Beaumont (U. S. Soil Conservation Service, 209 S. W. Fifth Avenue, Portland 4, Oregon) serving as Chairman of the Program Committee. Interested persons should get into touch with one of these or with Regional Chairman, Milton S. Sachs (2157 N. E. Tillamook Street, Portland, Oregon) or Regional Secretary, Vail P. Schermerhorn (c/o U. S. Weather Bureau, 320 Custom House, Portland 9, Oregon).

PACIFIC SOUTHWEST REGIONAL MEETING IN FEBRUARY, 1957—As noted in the April issue of the *Transactions*, this meeting will be held in Sacramento in February, 1957. The exact dates are still pending. Harlowe M. Stafford (3360 Fair Oaks Boulevard, Sacramento 21, California) is serving as general Chairman for the meeting, and Harvey O. Banks (431 Ross Way, Sacramento 21, California) and Jerome van de Erve (U. S. Weather Bureau, Box 2002, Sacramento, California) are arranging the programs for Hydrology and Meteorology respectively. Fred Strauss is Chairman of the Committee on Local Arrangements.

ELEVENTH GENERAL ASSEMBLY OF IUGG—The Eleventh General Assembly of the International Union of Geodesy and Geophysics will be held at the University of Toronto, Toronto, Ontario, Canada, September 4–14, 1957 (not August 5–17, 1957, as noted in the April issue). We call attention, however, to the note in the April issue regarding arrangements in other regards. J. A. Jacobs (Geophysical Laboratory, University of Toronto, Toronto, Ontario, Canada) is Secretary of the Canadian Committee on Arrangements, with J. Tuzo Wilson serving as Chairman, as noted in the April announcement.

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American Geophysical Union

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Crustal Movement in California and Nevada

C. A. WHITTEN

Generally we think of geodesy as a science in which absolute measurements are made primarily for the purpose of determining the size and shape of the Earth. An engineering application is made through the extension of geodetic networks of horizontal and vertical control for the development and conservation of our natural resources through federal programs of mapping, reclamation, reforestation, water power, highway construction, and many other activities associated with the growth of our country. In all of these varied programs the scientist or engineer asks for coordinates or elevations of points which may be used as references in the further development of his own work. It is fundamental to him that these reference points remain fixed.

Seismologists and geologists have suggested to geodesists that the same precise methods used in making these fundamental engineering surveys, previously mentioned, can be used in detecting small movements in the Earth's crust, particularly in areas subject to earthquakes. These small horizontal and vertical changes may be determined through a comparison of geodetic measurements made at regular intervals using differential techniques.

The history of some of the early work accomplished for this specific purpose has been described in earlier reports. Prior to 1946, the program of repeating surveys across areas of interest was hindered by lack of funds and the urgency of work in other areas for defense purposes. In the last few years it has been possible to accelerate this program of resurveying specific areas and now we are able to report on some of the results obtained during that time.

A major part of the effort has been directed toward the study of the systematic movement between the blocks on opposite sides of the San Andreas Fault. The oceanic block is creeping northwestward relative to the continental block at what might be considered a very uniform rate. In 1951, resurveys were made of two small networks, one near Monterey Bay and the other in the vicinity of San Luis Obispo, 60 or 70 mi southeast. Both of these nets, which are essentially arcs of triangulation crossing the fault zone, had been observed 20 years earlier. In the adjustment process, points at the northeast ends of the schemes were considered as fixed in position and all other points were permitted to seek new coordinates.

When triangulation is used to detect these small movements, it is essential that the base from which the triangulation is computed be in an area not subject to change. Because most of the areas are mountainous, taping is impractical. In future years the geodimeter can be used to check these fixed lines. If the base line changed, there would be a change of scale throughout the entire project with changes of position that would show radial movement away from or toward the base increasing in magnitude in direct ratio to the distance from the base, the direction depending upon whether the distance between the two ends of the base increased or decreased.

Mathematical adjustments were made of the surveys of the different periods using identical procedures. The differences in the coordinates represent the horizontal movement indicated during the 20-year interval. These are shown in Figures 1 and 2. The fixed points are beyond the limits of the diagrams. The shifts are larger than could be expected from errors of observation and the fact that the same pattern exists in both nets is a further confirmation of the reliability of the data showing this systematic movement. The vectors show a very uniform increase in length in proportion to the distance from the fixed end, transverse to the axis of the scheme. This direction plus the increase in amount of movement confirm the relative movement known to exist between the two sides of the fault zone. These linear displacements may be expressed in terms of angular distortion within the Earth's crust. Lines perpendicular to the fault zone change in azimuth and the lines parallel to the fault zone do not show any change in azimuth. This means that a

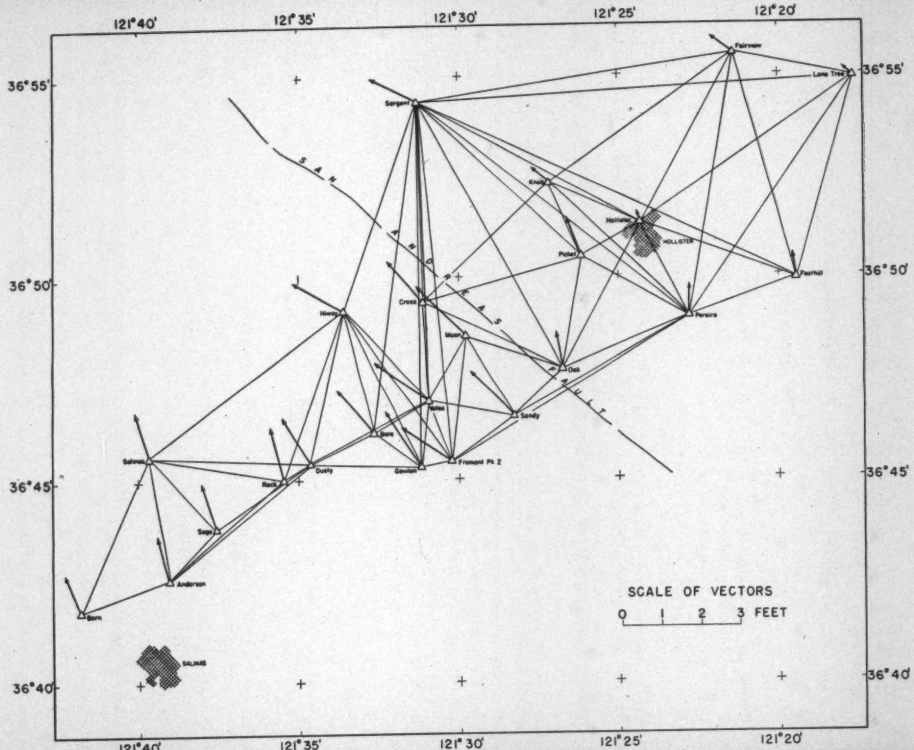

FIG. 1 – Triangulation in the vicinity of Monterey Bay; horizontal movement between surveys of 1930 and 1951

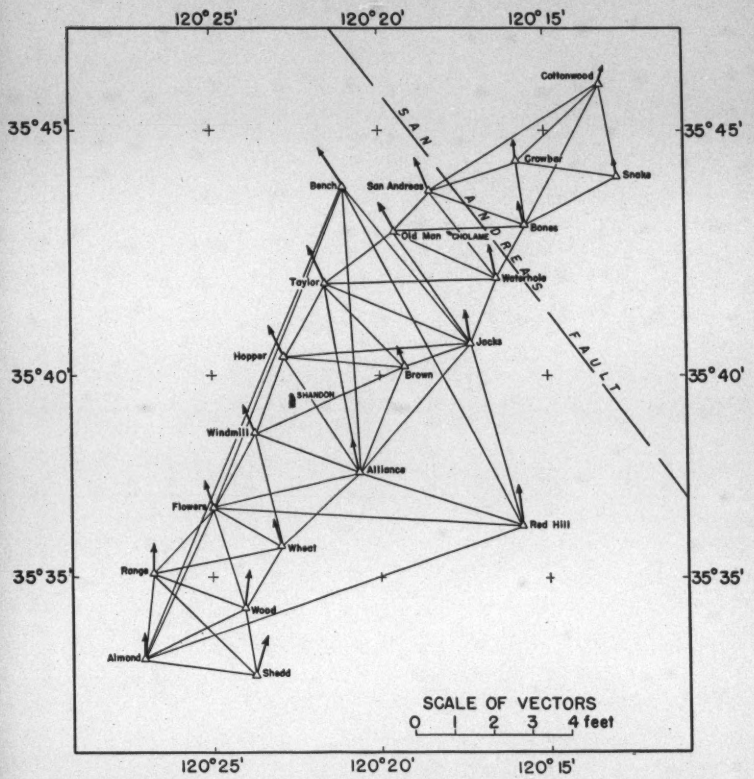

FIG. 2 – Triangulation northeast of San Luis Obispo; horizontal movement between surveys of 1932 and 1951

rectangular block of the Earth's crust in the fault zone would gradually become a parallelogram because of this small movement. In both resurveys this angular change of azimuth is about one second of arc every ten years. Naturally when the elastic limit of the Earth's crust is reached along the fault line, a major earthquake will be the result. A study of the data from these resurveys near Monterey Bay and San Luis Obispo does not indicate any major slipping along the fault; however, it is possible there may be some small minor displacements.

A very comprehensive resurvey over the Imperial Valley in Southern California was recently completed (Fig. 3). The survey was so extensive that we describe it as a network rather than an arc of triangulation. It is quite evident from the general appearance of such a network that it is strong and thus greater reliability can be placed on the results obtained than if single arcs had been used. This is an area in which there was a major earthquake in 1940 with very large displacements in the vicinity of El Centro and Holtville. Surveys made soon after that earthquake disclosed horizontal displacement of several feet, 12 to 14 in some places. These recent surveys were compared through this identical adjustment process with the surveys made a few months after the earthquake of 1940. The results of these two adjustments show that the points on the west

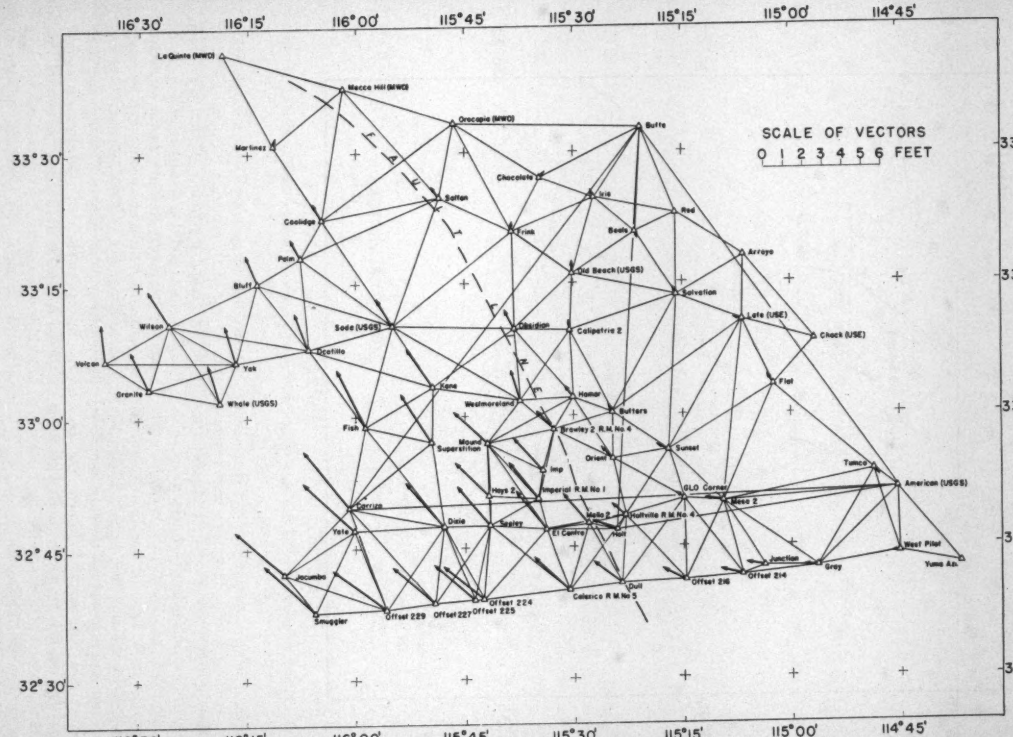

FIG. 3 – Triangulation in the Imperial Valley; horizontal movement between surveys of 1941 and 1954

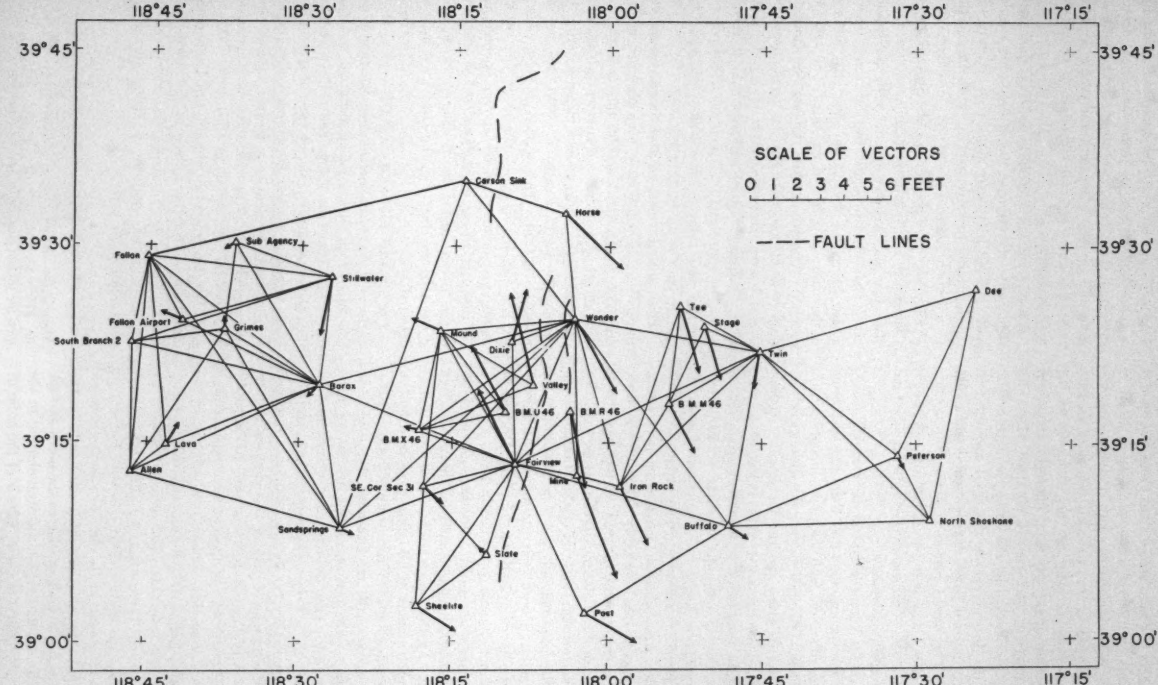

FIG. 4 – Triangulation in the vicinity of Dixie Valley, Nevada; horizontal movement between surveys of 1954 and 1955

side of the net have moved almost four feet relative to points on the east side over a span of about 14 years. When compared with positions of the original 1935 survey, the shift is almost six feet. If these linear quantities are reduced to the angular distortion the same figure of about one second per every ten years is obtained. The width of the area covered by this survey is much greater than the two previously described and for that reason the total linear displacement is somewhat larger. This would suggest that the fault zone is quite broad and that our repeat surveys should cover an area of sufficient breadth to map the total displacement accurately.

In addition to the systematic creeping movement, the vectors show that there has been some slippage along the fault line. The discontinuity in the vicinity of Brawley shows this quite clearly.

About ten years ago the Coast and Geodetic Survey, in cooperation with seismologists and geologists, established a definite schedule for reobservation of networks in these critical areas. This schedule has been maintained insofar as possible and, in addition, repeat surveys are made in other areas when an earthquake does occur. Such a case was a resurvey following the Kern County earthquakes of 1952 in the vicinity of Tehachapi and Bakersfield. This happened to be an area where previous surveys had been made; in fact, the latest one only a few months before the earthquake. A report on the findings of the resurvey is given in Bulletin 171 of the Division of Mines of California, published in 1955.

A somewhat similar situation occurred in Nevada. A triangulation party had been instructed to extend a first-order arc eastward from Fallon during the summer of 1954 (Fig. 4). Soon after this survey was completed, the area was disturbed by a very severe quake on December 16, 1954. The same party which had made the first survey went back into the area the following summer and reobserved the arc of triangulation. The vectors on the diagram show the shifts in position as disclosed by the technique of making two identical adjustments. A preliminary test was made to determine if there had been any movement of triangulation station Carson Sink, located on Job Peak in the Stillwater Range. If there was any displacement, it was less than that which can be detected by triangulation. Therefore, in the adjustment process this point was considered fixed as were the eastern and western ends of the arc. The vectors disclose the usual rebound effect, with the points on the west side of the fault shifting to the north and the points on the east side of the fault shifting to the south. The largest of these shifts is of the order of four feet and since they are opposite in direction, a total displacement of more than eight feet is indicated. Points which are closest to the fault line show the greatest movement and points 15 or 20 miles east and west of the fault show practically no movement.

There were vertical shifts as well which were detected by releveling. A line of first-order leveling had been run previously along U. S. Highway 50 which crosses the area east to west. In addition to the information obtained by the differences of leveling over the bench marks, the State Highway Department of Nevada had differences in elevation along the highway at intervals spaced much closer than that provided by the bench marks. These differences in elevation show that the floor of the valley dropped and was tilted. The west side dropped about five feet and the east side showed a drop of about two feet. Further north, releveling over a bench mark originally established by the U. S. Geological Survey indicated that there was a drop of approximately seven feet. This point is on the west side of Dixie Valley and near the eastern base of the Stillwater Range.

The horizontal and vertical displacements due to earthquakes which have been observed in this area are among the largest in this country ever determined by geodetic measurements, being only exceeded by the displacements measured after the earthquake at El Centro in 1940 and in San Francisco in 1906. This section of west central Nevada will be added to the areas over which repeat surveys will be made at regular intervals. By this means data will be collected so that any further displacements due to after-shocks or slow systematic movements in the crust itself may be detected.

The plans for continuation of this type of work in the next two years include reobservation of the triangulation in Owens Valley along the east side of the Sierra Nevada Range and reobservation of the coastal arc of triangulation extending from San Diego to San Francisco. The Owens Valley project is being reobserved after a 20-year interval and the coastal arc will provide data for comparison with measurements made in 1880, 1906, 1922–23, and 1946. This geodetic program, through periodic measurements on the surface of the Earth, will provide data for seismologists and tectonophysicists in their study of the forces at work in the interior of the earth.

U. S. Coast and Geodetic Survey, Washington, D. C.

(Manuscript received April 30, 1956; presented at the Thirty-seventh Annual Meeting, May 2, 1956; open for formal discussion until January 1, 1957.)

Vertical Motion in the Atmosphere and its Effect on VHF Radio Signal Strength

W. F. Moler and W. A. Arvola

Abstract—The hypothesis is proposed that the vertical gradient of the refractive index is strongly affected by the vertical motion in the atmosphere. It is shown that changes in this gradient are due principally to changes in the moisture stratification and temperature lapse rate resulting from the vertical velocity and its horizontal gradient within the air mass. Mean radio signal strengths are plotted against the time position of 500-mb troughs and ridges relative to the radio link. A series of 500-mb charts is given, with the vertical velocity field obtained by the Sawyer-Bushby method. The vertical velocity over two radio links is compared with the signal strength. Cross-sections taken through several of the troughs illustrate the stratification changes on the forward and rear sides of the troughs due to vertical motion.

Introduction—This report is concerned with the application of upper-level flow patterns and vertical-motion fields for forecasting VHF field strength. In earlier work on radio propagation it has been recognized that the vertical gradient of the refractive index (hereafter called the N-gradient) is influenced by the vertical motion. In regions where the vertical motion is upward, the atmosphere is well mixed and usually subrefractive and the signal strength in the diffraction region is weak. Where sinking motion occurs, the atmosphere becomes stratified and the signal strength rises.

Until recently there has been little direct, quantitative application of vertical motion in forecasting. As a result of the operational use of numerical weather-prediction methods, the Joint Numerical Weather Prediction Unit in Suitland, Maryland, will soon begin issuing forecast fields of vertical motion at 800 and 550 mb on a routine basis in addition to prognostic constant-pressure charts. This material will be available to the forecaster in the field.

Over oceanic and other areas of the world for which numerical prediction charts will not be available, some sort of synoptic procedure is required. Recent synoptic investigations and development of weather-prediction models have greatly increased our knowledge about the three-dimensional motions in the atmosphere. The aerologist can now compute quantitative values of the vertical velocity by using vorticity concepts applied to readily available synoptic data.

An interval of five days in winter was selected for detailed study of the variation of signal strength with changes in the synoptic situation. During this period, a series of six diverse upper-level troughs passed over the eastern United States. The field of vertical motion associated with these troughs was computed, and vertical cross sections through the troughs were constructed for study of the moisture field.

The radio data used in this study were from two links in Illinois, and from two links in Ohio, as described in Table 1.

Theory—The ray curvature of radio waves less than ten meters in length is numerically equal to the N-gradient taken normal to the direction of propagation. The ray is bent toward higher values of N. It is observed, and can be shown theoretically, that the signal strength in the diffraction zone is some function of the N-gradient; high signals occur with large negative gradients, weak signals with a well mixed atmosphere. It follows that the local change of signal strength must be functionally related to the rate of change of the N-gradient with time.

The modified index of refraction N is given by

$$N = (n - 1) \times 10^6 = \frac{78p}{T}\left(1 + \frac{7.7m}{T}\right) \quad (1)$$

where n is the index of refraction, p is the pressure in mb, T is the temperature in degrees Kelvin, and m is the mixing ration in grams of water vapor per kilogram of dry air.

The local change of N-gradient is given by

$$\frac{\partial}{\partial t}\left(\frac{\partial N}{\partial z}\right) = \left(\frac{\partial p}{\partial t}\frac{\partial^2 N}{\partial z\,\partial p}\right) + \left(\frac{\partial N}{\partial p}\frac{\partial^2 p}{\partial z\,\partial t}\right) + \left(\frac{\partial T}{\partial t}\frac{\partial^2 N}{\partial z\,\partial T}\right) + \left(\frac{\partial N}{\partial T}\frac{\partial^2 T}{\partial z\,\partial t}\right) + \left(\frac{\partial m}{\partial t}\frac{\partial^2 N}{\partial z\,\partial m}\right) + \left(\frac{\partial N}{\partial m}\frac{\partial^2 m}{\partial z\,\partial t}\right) = a_2 + b_2 + c_2 + d_2 + e_2 + f_2 \quad (2)$$

(Here and below, the short form represents the full equation term for term, and the subscripts denote equation numbers.) All time derivatives are local changes of the physical properties.

TABLE 1 – *Description of radio links monitored*

Station	Location	Frequency	Monitored	Dist.	Transmitter height	Receiver height
		Mc/s		mi	ft	ft
WBKB-TV	Chicago	71.75	Urbana	127	688	90
WENR-TV	Chicago	179.75	Urbana	127	668	90
WCOL-FM	Columbus	92.3	Hudson	121	380	30
WJB-FM	Detroit	96.3	Hudson	114	480	31

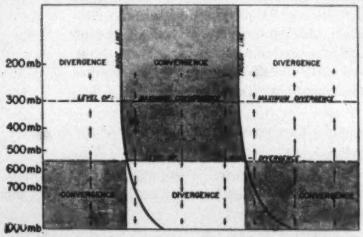

FIG. 1 – Model of the trough and ridge system with distribution of vertical velocity and divergence from 1000 mb to 100 mb

Terms a_2 and b_2 amount to less than 1 N-unit/km in three hours for local pressure changes exceeding the upper limits found in nature, and so contribute a negligible amount toward changes in N-gradient.

The N-gradient change resulting from changes in mean temperature or mean moisture content of the column of air (terms c_2 and e_2) is small. In a standard atmosphere at 900 mb, the N-gradient changes at the rate of two N-units/km hr for a change in mixing ratio of 1 gm/kg hr and 0.87 N-units/km hr for a mean temperature change of 1°K/hr.

The remaining terms d_2 and f_2 show the N-gradient change resulting from changes in the temperature and moisture lapse rates. In the lower 4000 ft of the atmosphere $\partial N/\partial T \approx -1$ so that the sign and magnitude of d_2 is given by $\partial^2 T/\partial z\,\partial t$. An expression for the local change of the temperature lapse rate is

$$\frac{\partial}{\partial t}\left(\frac{\partial T}{\partial z}\right) = \left(\frac{\partial^2 T}{\partial z\,\partial t}\right)_N + \frac{\alpha}{c_p}\left(\frac{\partial^2 p}{\partial z\,\partial t} + \frac{\partial v}{\partial z}\frac{\partial p}{\partial s} + v\frac{\partial^2 p}{\partial s\,\partial z}\right) - \frac{\partial v}{\partial s}\frac{\partial T}{\partial s} - v\frac{\partial^2 T}{\partial z\,\partial s} - \frac{\partial w}{\partial z}(\gamma_p - \gamma) + w\frac{\partial \gamma}{\partial z} = a_3 + b_3 - c_3 - d_3 - e_3 + f_3 \quad (3)$$

where $(\partial^2 T/\partial z\,\partial t)_N$ is the nonadiabatic term involving radiative and conductive processes and will be disregarded in this report. The symbol γ is the environmental temperature lapse rate; γ_p is the adiabatic process lapse rate; v the velocity along the streamline s; w the velocity along the vertical coordinate z; α is the specific volume; and c_p is the specific heat of air at constant pressure.

When geostrophic flow is stipulated, the second and third parts of b_3 vanish and the first part, arising from the vertical gradient of pressure change, is several orders of magnitude smaller than other terms and can be ignored.

Terms c_3 and d_3 are functions of the horizontal temperature gradient and the vertical change of the horizontal temperature gradient. When reasonable values are substituted in (3) it is found that contributions from c_3 and d_3 outweigh all others. In order to determine the total advective contributions over an interval of several hours, it is necessary to consider changes in the horizontal temperature gradient with time.

$$\frac{\partial}{\partial t}\left(\frac{\partial T}{\partial s}\right) = \frac{\partial}{\partial t}\left(\frac{\partial T}{\partial s}\right)_N - \frac{\partial v}{\partial s}\frac{\partial T}{\partial s} - v\frac{\partial^2 T}{\partial s^2} - \frac{\partial w}{\partial s}(\gamma_p - \gamma) + w\frac{\partial \gamma}{\partial s} = a_4 - b_4 - c_4 - d_4 + e_4 \quad (4)$$

Again the nonadiabatic term a_4 will be disregarded. The advective terms b_4 and c_4 show the change of

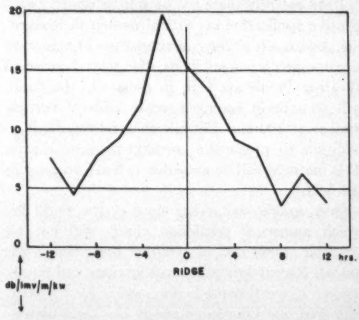

FIG. 2 – Average signal strength for time positions of 500-mb troughs and ridges, Chicago-Urbana link, 179.75 mc

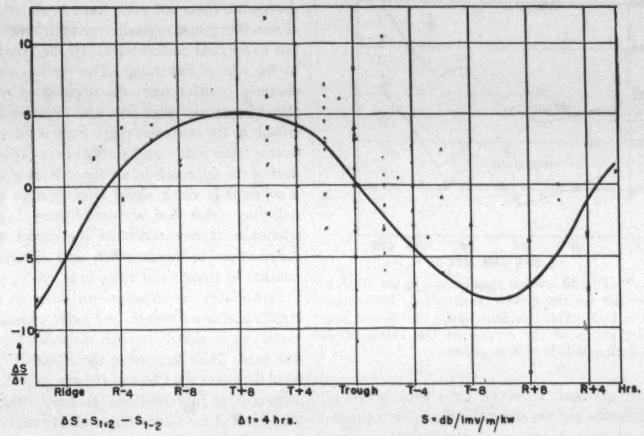

FIG. 3. – Rate of change in the signal strength in relation to the time position of the 500-mb trough and ridge lines, Chicago-Urbana link, 179.75 mc

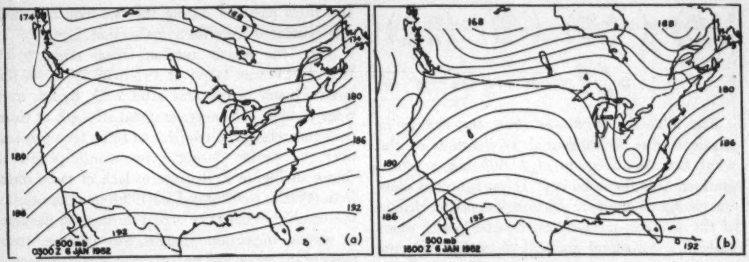

FIG. 4 – 500-mb maps for (a) 03h00m and (b) 15h00m GCT January 6, 1952

gradient due to acceleration along the streamline and to advection of a different horizontal temperature field. Term d_4 shows how the isothermal surfaces become tilted from the horizontal when there is a change in the horizontal gradient of the vertical velocity along the horizontal streamline. Term c_4 expresses the change of horizontal temperature gradient as a function of the vertical advection of the horizontal difference in the temperature lapse rate.

When the air mass is initially baratropic, that is, $d\vec{T}/ds = 0$, terms e_3 and f_3 show that a change in lapse rate will occur upon the advent of vertical motion. When there is a horizontal gradient of vertical motion, barotropy will be destroyed, according to d_4, and all other terms of (3) and (4) become operative and would increase the rate of change of lapse rate.

The partial dependence of the N-gradient change upon the change in the moisture lapse rate was given by f_2. The instantaneous change of the vertical moisture gradient can be written

$$\frac{\partial}{\partial t}\left(\frac{\partial m}{\partial z}\right) = \frac{\partial}{\partial t}\left(\frac{\partial m}{\partial z}\right)_c - \frac{\partial v}{\partial z}\frac{\partial m}{\partial s} - v\frac{\partial}{\partial z}\left(\frac{\partial m}{\partial s}\right) - w\frac{\partial^2 m}{\partial z^2} - \frac{\partial w}{\partial z}\frac{\partial m}{\partial z} = a_5 - b_5 - c_5 - d_5 - e_5 \quad (5)$$

The nonconservative change a_5 will be disregarded. Again, as for the change in the temperature lapse rate, the advective terms b_5 and c_5 make the greatest contribution to the change in the vertical

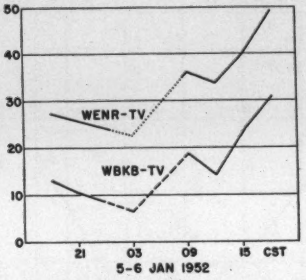

FIG. 5 – Hourly median signal strength for WENR and WBKB for the period January 5–6, 1952; time shown is CST (90th meridian time); the dotted and dashed portions of the curves are the extrapolated values during periods of radio silence

moisture gradient. However, for a finite period of time it can be shown, as for the changing temperature field, that changes in the horizontal gradient of moisture must be taken into account. These changes are given by

$$\frac{\partial}{\partial t}\left(\frac{\partial m}{\partial s}\right) = \left(-\frac{\partial v}{\partial s}\frac{\partial m}{\partial s}\right) - \left(v\frac{\partial^2 m}{\partial s^2}\right) - \left(\frac{\partial w}{\partial s}\frac{\partial m}{\partial z}\right) - w\frac{\partial^2 m}{\partial z\,\partial s} = -a_6 - b_6 - c_6 - d_6 \quad (6)$$

The advective terms b_6 show the change of gradients due to tangential acceleration of the wind and to advection of a differing moisture gradient over the radio link. Terms c_6 and d_6 show the change of gradient as a function of the change of tilt of the m-surfaces experienced locally when there is a horizontal gradient of vertical velocity or a horizontal gradient of moisture stratification or both. From (5) and (6), it can be seen that when the initial horizontal moisture gradient is zero, only terms d_6 and e_6 are operative in the first instant. However, when $\partial w/\partial s \neq 0$, the left side of (6) will not be zero and in the next instant all terms of (5) and (6) become operative.

In summary, the N-gradient (and radio signal strength) should decrease during periods of rising motion, increase during periods of sinking motion. The rate of rise and fall depends most strongly on the initial temperature and moisture stratification and the horizontal gradient of vertical velocity.

Atmospheric model—A simple model of the three-dimensional motion in a moving-wave system was assumed in order to make a qualitative check of the field strength dependency upon vertical motion. The model assumes a midtropospheric level of non-divergence (near 600 mb); there is, above the level of nondivergence, mass divergence from the trough line to the next downstream ridge, and convergence to the rear of the trough. The vertical velocity is assumed positive from the upper-level trough to the downstream ridge line, and negative from the trough to the upstream ridge. Such a wave passing over a radio link would then cause a falling signal during the approach of an upper-level trough and a continually rising signal after passage until the following ridge line arrives. Figure 1 shows a schematic representation of the model with the distribution of convergence and divergence in relation to trough and ridge lines.

Preliminary investigation—In order to check a large number of trough and ridge passages with variations in signal strength the following scheme was used: Time sections of the 18,000-ft (5.5 km) wind flow over the Chicago-Urbana radio link were prepared for July 1951 and January 1952. Winds were plotted for Green Bay and Milwaukee, Wisconsin, Joliet and Rantoul, Illinois, and Evansville, Indiana, along north-south coordinates at six-hour intervals. The time of all 18,000-ft trough and ridge passages during the two-month period was estimated from the cross section.

Next, the hourly median signal strength of WENR-TV was taken at two-hour intervals for twelve hours before and after each trough and ridge passage. The average signal strength at time positions relative to trough and ridge lines passing over the station during a two-month period is shown in Figure 2. Because of lack of radio data from 00h00m to 09h00m CST (90th meridian time) the complete change of signal during the passage of several important troughs was missing, thus making the graph less smooth than would normally

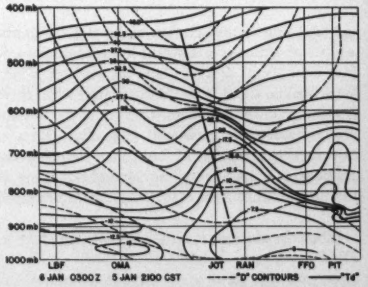

FIG. 6 – Vertical cross-section along the line North Platte — Omaha — Joliet — Wright-Patterson — Pittsburgh for 03h00m GCT January 6, 1952

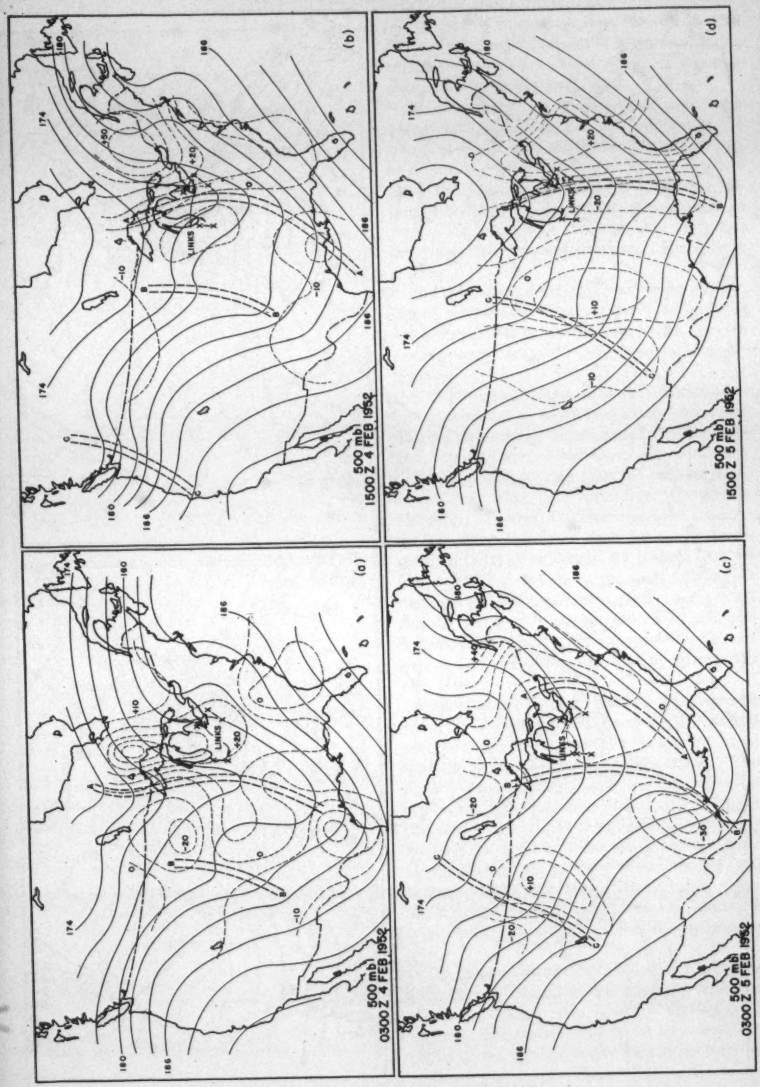

FIG. 7(abcd)—500-mb charts, Feb. 4–5, 1952

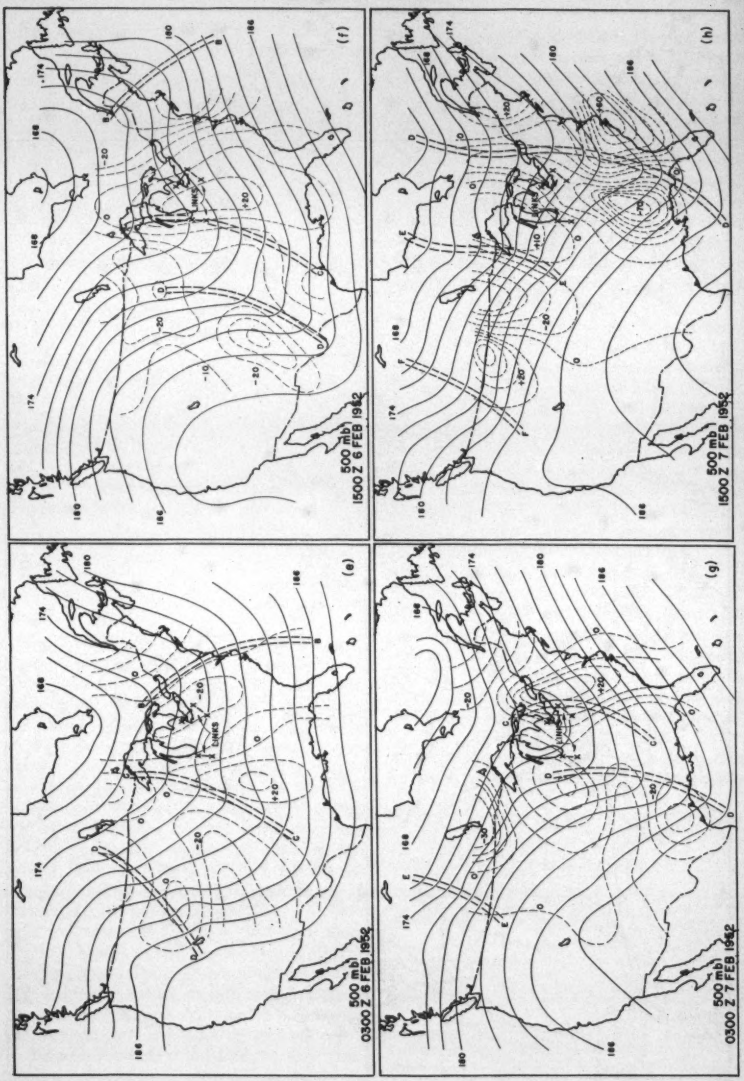

FIG. 7(efgh)—500-mb charts, Feb. 6–7, 1952

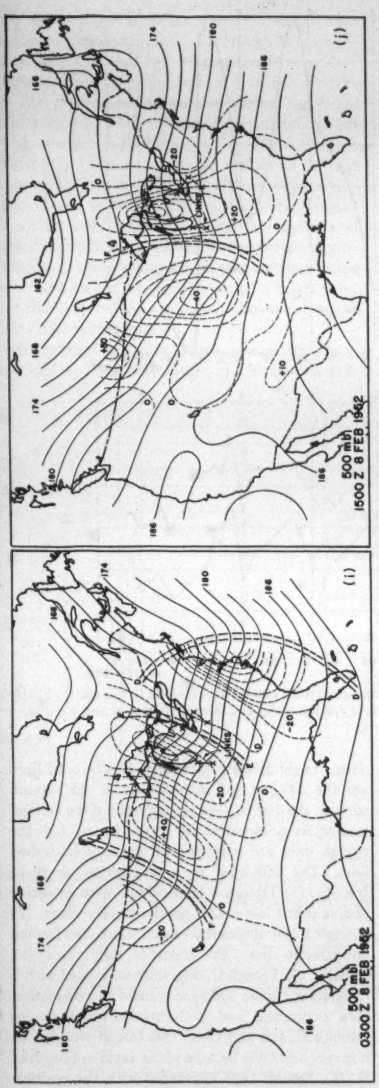

FIG. 7(ij)—500-mb charts, Feb. 8, 1952

be expected. It is apparent from Figure 2 that, in the mean, signals do reach a minimum during trough-line passages and the maximum signal is associated with upper-level ridges.

From the same data the rate of signal-strength change with respect to the time position of the trough and ridge lines was determined and plotted as shown by Figure 3. The wide spread of points along the trough-line coordinate show that, although in the mean the vertical velocity may be zero at the trough line, there are large individual departures from the assumed model of atmospheric motions.

The two-month mean data were taken without regard to synoptic weather types. The 18,000-ft waves varied greatly in amplitude, length, speed of motion, and association with surface pressure systems.

A hand-picked weather situation, wherein there was a minimum of advective change, yet during which a major upper trough passed over the radio link, was used next. The 500-mb map for 03h00m GCT on January 6, 1952 (Fig. 4a) shows a major trough along a line from Green Bay, Wisconsin to Columbia, Missouri. Polar air was over the links at all levels, surface flow was northerly, and stratus clouds covered all of Illinois. By 15h00m GCT on January 6 (Fig. 4b) the upper-air trough moved eastward to a line from Buffalo to Atlanta. During this 12-hour period the surface winds remained northerly, cloudiness continued over Illinois, and no low-level changes in temperature or humidity took place.

Figure 5 shows the hourly median signal strength curve for WENR during this period. (The dashed portion of the curve is an extrapolation of signal strength during the period of radio silence.) The signal fell from midafternoon until the time when the transmitter shut down on January 5, yet by the time of broadcast resumption the following morning the signal had risen ten db and continued to rise (except for a midafternoon diurnal dip) throughout the day. Apparently the time of the upper-trough passage at 03h00m on January 6 would coincide with the time of lowest radio-signal level.

The physical change in stratification causing the reduction in refractivity through the trough is shown by the east-west vertical cross section in Figure 6. The dashed lines in the section are isopleths of the pressure-height departures from the standard atmosphere. These delineate the trough and show the increasing intensity with height. The dew-point isotherms (solid lines) show how the

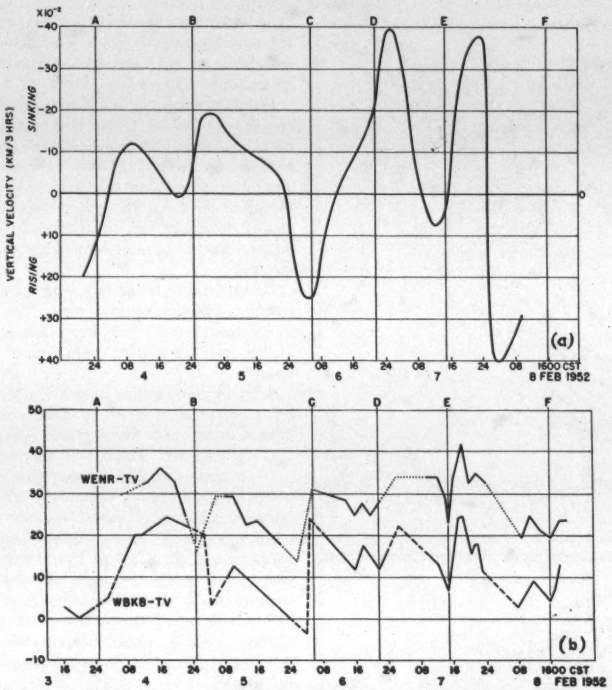

FIG. 8 – February 4–8, 1952; (a) time graph of the instantaneous vertical motion over the link in Illinois; (b) hourly median signal strength above the standard diffracted field for the radio link between Chicago and Urbana, Illinois

moisture stratification in the lower levels disappears with the approach of the upper-level trough and its associated vertical-motion field. The close coupling between the loss of refractivity with the upper-level trough indicates that a good prognosis of the upper-level flow is essential for making a good radio-propagation forecast.

The February 4–8 series with diverse troughs— The period of February 4 to 8, 1952, was chosen for a typical winter series. The mean flow at 500 mb during these days was characterized by a ridge over the western part of the country and a trough over the eastern regions. A series of short-wave troughs move around the top of the ridge into the Great Plains area. During the five-day interval there were six troughs which moved through Illinois and Ohio. Figure 7 shows the twice-daily 03h00m and 15h00m GCT 500-mb maps for this series with troughs labeled A through F. The solid lines are the 200-foot (61 m) contours of the 500-mb surface, the dashed lines are isopleths of the vertical motion in dekameters per three hours, and the trough lines are indicated by the double dashed lines. The following is a description of these troughs: (1) Trough A is associated with an active double-celled low center on the surface chart. (2) Trough B is a nonfrontal trough which had formed downstream from the unstable ridge over the Rockies. (3) Trough C, originally associated with a dissipating Pacific occlusion, caused the generation of a nonfrontal low in Nebraska which moves through Illinois and Ohio; this trough weakens as it moves into Ohio because of the rapid approach of D. (4) Trough D is associated with the position of the 500-mb warm front, along the forward edge of the ridge. (5) Trough E is associated with a

rapidly moving Alberta low which moved eastward north of the Great Lakes. (6) Trough F is associated with a surface low which moved from Montana eastward through northern Illinois and Ohio.

The field of vertical motion during the period February 4–8, 1952—The field of vertical motion is shown with dashed lines on the 500-mb maps in Figure 7. Positive values are regions of upward motion and negative values regions of sinking motion. These vertical-motion values were obtained by hand computation applying the methods of the Sawyer-Bushby numerical-weather-prediction model. The values are the instantaneous vertical velocities for the map time and are a mean value for the 500-mb level, which has been taken as the level of nondivergence.

In the maps in Figure 7 there is, in general, rising motion ahead of the troughs and sinking motion to the rear of troughs. This simplified distribution of vertical velocity is often distorted by the complex thermal patterns. The fact that the numerical-weather prediction methods take into account such factors as the thermal patterns which are associated with the pressure features but not always intuitively obvious to the forecaster, makes their application attractive.

The field of vertical motion in connection with the troughs shows up when the troughs are yet minor and located upstream from the link. As the troughs increase in amplitude the vertical motion fields intensify. Even from a synoptic forecasting point of view, there is prognostic value in having clues to future development upstream in the upper-level flow.

The time graphs of instantaneous vertical motion for the links in Illinois and Ohio are shown in the

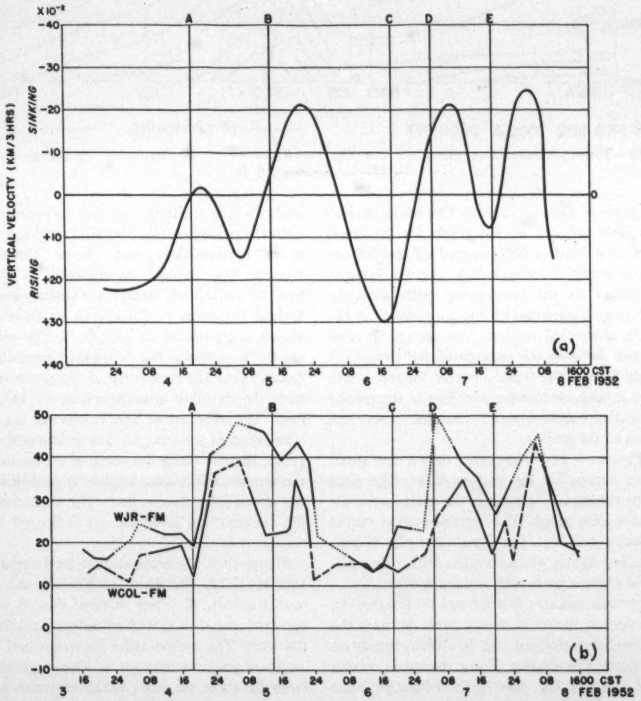

FIG. 9 – Feb. 4–8, 1952; (a) time graph of the instantaneous vertical motion over the links in Ohio; (b) hourly median signal strength above the standard diffracted field for the radio links in Ohio

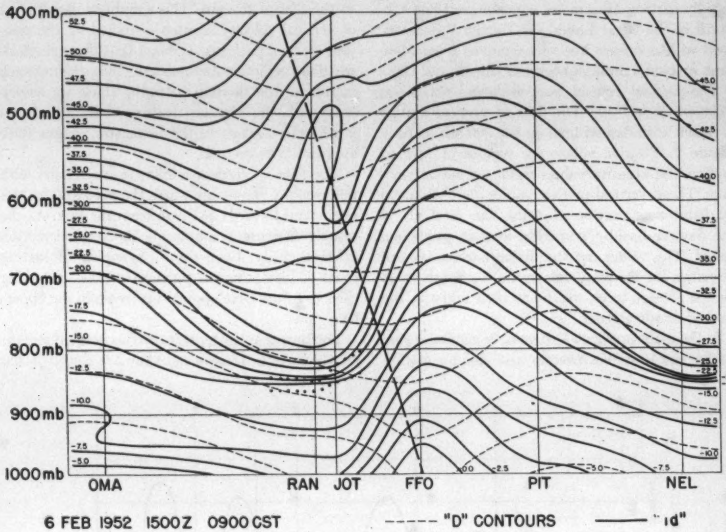

FIG. 10 – Vertical cross-section along the line Omaha—Rantoul—Wright-Patterson—Pittsburgh—Lakehurst for 15h00m February 6, 1952

upper parts of Figures 8 and 9. The instantaneous values were entered on the graph for the times 09h00m and 21h00m CST as read off the 500-mb charts in Figure 7 for each link, and the interpolated values for the intervening hours were obtained from knowledge of the movement of the isopleths of vertical motion. The vertical lines on the graph indicate the passage of the troughs A through E over the links. Positive values denote upward motion (below the zero line in the graph) and negative values downward motion (above the zero line in the graph).

In Figures 8 and 9 are also shown the signal strength curves for the various links. The time scale for the signal strength is the same as for the vertical-motion graph. The vertical-motion curves agree quite well with the signal strength; in general, falling signals are associated with rising motion and rising signals with sinking motion.

The vertical moisture field through the troughs—In the section on theory it was pointed out how the refractive-index gradient was dependent largely on the moisture distribution. For a change in mixing ratio of 1 gm/kg the value of the refractive index N changes by about seven units, whereas for a temperature change of 1°C, N changes by one unit. To investigate the vertical moisture gradients with the passage of the 500-mb troughs, a series of space cross-sections was drawn through the troughs. One example of cross-section along the line of radiosonde stations Omaha—Rantoul—Wright-Patterson — Pittsburgh — Lakehurst is shown in Figure 10 for trough C. The solid lines are the isopleths of the dewpoint temperature, the dashed lines the departure of the pressure-height from the standard atmosphere, or the so-called D lines. The latter set of lines brings out the vertical orientation of the troughs. The radiosonde data for Joliet, Illinois, which lies north of the cross-section, was entered in the cross-section by projection along the upper-level stream flow. The base and top of the temperature inversion are indicated by continuous dotted lines.

Figure 10 is the cross-section for February 6 at 15h00m GCT. Trough C at 500 mb was located over Rantoul. A strong vertical flux of moisture occurred ahead of C and subsidence conditions to the west. The temperature inversion had a good moisture gradient through it. The response of the radio signals to the onset of this inversion was pronounced in the Illinois links, but by the time trough C moved into the Ohio area these post-

trough conditions are less pronounced in Ohio because of the acceleration of trough D.

Conclusion—This work, though confined to a brief period, indicates that the upper-level troughs and ridges and their attendant fields of vertical motion cause changes in the signal strength for VHF radio. By utilizing the new data mentioned at the outset, signal-strength forecasts will become possible, but the relation between vertical motion and signal strength needs to be developed more fully. It would be desirable to have data on the moisture content included with the vertical-motion fields, because of its important effect on the refractive-index gradients. This need is brought out in the problem of forecasting for the western side of troughs, where subsidence inversions are usually found. The height of an inversion, its intensity, and the moisture gradient through the inversion are the important forecast parameters. In relatively dry air a temperature inversion may form, but in the absence of a moisture gradient through it, there would be no significant discontinuity in the refractive index.

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Cl′ and SO_4'' Content of Atmospheric Precipitation in USSR: A Summary

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Abstract—The relative abundance of Cl′ and SO_4'' anions in the atmospheric precipitation of USSR is discussed in the present summary. In addition, the amounts of HCO_3', NO_3', $Na^{\cdot}$, $Ca^{\cdot\cdot}$, $Mg^{\cdot\cdot}$, and $NH_4^{\cdot}$ ions in the atmospheric precipitation are also presented.

Review of the Russian literature indicates that the average SO_4'' content of atmospheric precipitation in USSR is about twice as high as that of Cl′ anion. This leads to a conclusion that the major portion of SO_4'' anions is not of marine origin.

Introduction—According to S. V. Dobroklonskiy and P. B. Vavilov [*Alekin*, 1953, p. 121], a 50-mg raindrop falling from an altitude of one km 'washes' 16.3 l of air. Thus, one liter of rain water 'washes' approximately 3.26×10^6 l of air. The composition of atmospheric precipitation, therefore, depends not only on the composition of atmospheric water, but also on the amount of dust in the air, size of precipitation, altitude of clouds, wind direction, preceding weather conditions, temperature, and type of precipitation (rain or snow). It is also regretful that the present-day techniques of collecting atmospheric precipitation do not eliminate the influence of mechanical admixtures brought by the wind.

L. K. Blinov [*Alekin*, 1953, p. 122] determined that 52 tons of salts are carried across one km of Caspian Sea shoreline in 24 hours when the wind speed is 6 m/sec; and up to 185 tons, when the wind speed is 10 m/sec. At normal conditions, however, the marine salts are not carried beyond a narrow near-shore zone. For example, Dobroklonskiy and Vavilov [*Alekin*, 1953, p. 122] found that the coarse droplets of sea water settle within 200–250 m from the shore; and the salt content of atmospheric precipitation becomes more or less constant beyond this narrow zone.

Cl′ and SO_4'' content of atmospheric precipitation in USSR — *Vityn′* [1911] made a comprehensive study of the Cl′ and SO_3 content of atmospheric precipitation in the European USSR (Tables 1 and 2). The examination of Table 1 reveals that greater variations occur in the amount of SO_4'', which depends largely on the proximity to large cities and industrial centers. Table 2 also shows that the amount of SO_4'' increases during the winter months, which is probably caused by the larger consumption of coal for heating purposes. On the other hand, the largest amount of Cl′ in the atmospheric precipitation near Leningrad was observed during the predomination of shoreward winds, namely during the spring and autumn.

Considerably higher amounts of Cl′ and SO_4'' are found in the atmospheric precipitation from areas having saline soils. For example, according to N. I. Usov [*Alekin*, 1953, p. 124] in the lower area along the Volga (Baskunchak, El′ton, Aleksandrovsk-Gay, and Novouzensk stations) the average amount of salts is equal to 205.9 mg/l; with HCO_3', $Ca^{\cdot\cdot}$, $Mg^{\cdot\cdot}$, $K^{\cdot} + Na^{\cdot}$, Cl′, and SO_4'' ions having concentrations of 61, 25.5, 3.9, 35, 36.5, and 44 mg/l, respectively. The amount of HCO_3' is characteristically higher than either Cl′ or SO_4'' contents. In several cases, however, the Cl′ content was found to be as high as 500–600 mg/l (Baskunchak station). The above results also appear to indicate a large mechanical admixture.

Wide variations in the chemical composition of atmospheric precipitation in USSR have been observed by *Burkser* and others [1952]. The mineralization was found to be highest in the areas situated near seas and saline basins. For example, in the Arctic stations the sum of ions was equal to 17–79 mg/l, with the average Cl′, SO_4'', and HCO_3' contents being equal to 8.88, 8.77, and 18.3 mg/l, respectively. The mineralization of atmospheric precipitation was somewhat lower on Sakhalin Island, whereas around El′ton Lake and Aral Sea the mineralization was very high. The lowest amount of mineralization, on the other hand, was found in high-mountain areas and Franz-Josef Land.

The results of chemical analysis of atmospheric precipitation in the northwestern areas of USSR (Table 3), obtained by *Burkser* and others [1952], were in close accord with those obtained by *Vityn′* [1911].

The average composition of the atmospheric precipitation in USSR, which is based on analysis of 190 samples from 41 hydrometeorological stations, is presented in Table 4 [*Durov* and *Fedorova*, 1955]. About half of these stations were located along the shores of Black Sea, Azov Sea, Arctic Ocean, and Sea of Okhotsk. Identical results were reported by *Burkser* and others [1952].

The Cl′ and SO_4'' contents of snow water are

TABLE 1 – *Yearly average of Cl′ and SO_3 content of atmospheric precipitation in European USSR* [after *Vityn′*, 1911]

Location	Period		Precipitation		Cl′	SO_3
	From	To	No. of days	Amount		
				mm	mg/l	mg/l
Leningrad, Institute of Forestry	Apr. 1909	Mar. 1910	225	645.5	3.56	12.21
Leningrad, Okhtensk Forestry	May 20, 1909	May 1, 1910	209	669.1	2.36	11.87
Pavlovsk Observatory	Mar. 21, 1909	Mar. 28, 1910	229	521.5	1.57	3.52
Luga, Zapol′sk station	May 11, 1909	Apr. 1, 1910	..	486.0	3.01	2.22
Smolensk district, Engel′gard experimental station	Apr. 15, 1909	Apr. 1, 1910	255	660.0	3.06	1.00
Mariupol′, Experimental Forestry	May 1, 1909	May 1, 1910	93	339.2	3.77	16.26
Tula district, Shatilov Experimental Station	Apr. 1, 1909	Apr. 1, 1910	141	476.4	1.83	1.92
Samara district, Borov Experimental Station	Apr. 19, 1909	Apr. 1, 1910	124	541.2	1.95	1.06

TABLE 2 – *Cl′ and SO_3 content of atmospheric precipitation during different times of the year, 1909–1910* [after *Vityn′*, 1911]

Leningrad, Institute of Forestry				Tula district, Shatilov Experimental Station		
Date of collection		Cl′	SO_3	Date of collection	Cl′	SO_3
From	To					
1909		mg/l	mg/l	1909	mg/l	mg/l
Feb. 20	Mar. 9	2.10	..	Apr.	2.80	1.03
Mar. 29	Apr. 27	3.22	16.06	May	0.70	2.33
Apr. 28	May 14	15.68	30.60	June	0.40	1.03
May 14	June 20	3.43	13.55	July	0.70	1.30
June 20	July 13	2.17	4.74	Aug.	1.10	4.33
July 14	July 17	1.40	6.38	Sep.	5.50	5.07
July 18	Aug. 10	1.05	3.26	Oct.	3.60	3.64
Aug. 10	Aug. 11	0.98	1.72	Nov.	0.96	2.20
Aug. 12	Sep. 9	2.70	8.16	Dec.	5.80	6.38
Sep. 10	Oct. 5	2.94	6.96	1910		
Oct. 6	Oct. 31	2.80	14.03	Jan.	20.10	7.34
November		2.60	17.32	Feb.	9.00	7.72
December		1.54	10.60	Mar.	2.90	6.93
1910						
January		2.52	12.20			
February		3.04	32.92			
March		19.32	25.44			
April		4.70	19.26			
May		2.90	9.04			

markedly lower than those of rain water. As an example, the findings of *Voronkov* [1951b] are presented in Table 5.

Conclusions—On the average, the SO_4'' content

TABLE 3 – *Ionic composition of atmospheric precipitation in north-western areas of USSR* [after *Burkser* and others, 1952]

Ion	Content
	mg/l
Cl′	3.62
SO_4''	4.66
HCO_3'	12.45
$Na^{\cdot}$	2.30
$Ca^{\cdot\cdot}$	3.21
$Mg^{\cdot\cdot}$	1.33

TABLE 4 – *Average ionic composition of atmospheric precipitation in USSR* [after *Durov* and *Fedorova*, 1955]

Ion	Content
	mg/l
Cl′	5.46
SO_4''	9.17
HCO_3'	18.20
NO_3'	1.70
$Na^{\cdot}$	5.12
$Ca^{\cdot\cdot}$	4.82
$Mg^{\cdot\cdot}$	1.74
$NH_4^{\cdot}$	0.21

TABLE 5 – *SO_4'' and Cl′ content of atmospheric precipitation in Valday district in 1948* [after *Voronkov*, 1951b]

Location	Date of sample collection	Depth of snow	Snow layer collected	SO_4''	Cl′	SO_4''/Cl′
	1948	cm	cm	mg/l	mg/l	
Usad′evskiy basin	Mar. 27	58	0–44	2.0	0.4	5.0
Valday lake	Mar. 28	33	0–12	1.5	0.6	2.5
Arkhireyskiy River basin	Mar. 29	38	0–12	1.0	0.2	5.0
Arkhireyskiy River basin	Mar. 29	38	12–25	2.4	0.3	8.0
Taezhnyy basin	Mar. 30	58	0–52	2.7	0.4	6.2
Priusadebnyy basin	Mar. 31	70	0–68	1.3	0.7	1.9

of atmospheric precipitation in USSR is twice as high as that of Cl′ anion. This predominance of SO_4'' anions appears to be of considerable significance in determining their origin. Apparently, the major portion of SO_4'' anions is not of marine origin, because the SO_4'':Cl′ ratio does not even approach 0.14 (ratio in sea water).

Besides sea water, the SO_4'' anions could owe their origin to (1) volcanic emanations, (2) industrial gases, (3) biochemical processes occurring during decomposition of organic matter with evolution of H_2S, and (4) salts lifted together with dust from the Earth's surface [*Alekin*, 1953, p. 125].

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Lithium Chloride Dewcel Properties and Use for Dew-Point and Vapor-Pressure Gradient Measurements

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Abstract—The lithium chloride Dewcel covered under the Foxboro Company patent number 2,359,278 has been modified slightly and used to measure small dew-point or vapor-pressure gradients above a crop. The advantage of the Dewcel is that the relative error of the measurement is the same at all dew points and that Dewcel data are conveniently reduced to dew-point and vapor-pressure data. The disadvantage of the Dewcel is its large absolute error which often may be as large as the dew-point gradient measured. The Dewcel modification and the equipment for excluding the absolute error of the Dewcels from the dew-point gradient measurement are reported. In order to operate the Dewcel suitably, several of the Dewcel characteristics have been determined. The effect of ventilation and changes in air temperatures upon the Dewcel temperature and the slope of the dew-point — Dewcel-temperature curve at various Dewcel temperatures above ambient are given. Two methods for Dewcel calibration are reported. A scheme for generating constant dew-point air at rates of 20 liters per minute is given.

For each dew point or absolute humidity of air there exists only one temperature at which a saturated solution of LiCl (excess salt present) will be in equilibrium with the air, neither absorbing or evaporating water. This temperature, called the LiCl dew point, computed from data taken from *International Critical Tables* [1928, p. 368], is shown in Figure 1 plotted against dew point over water and ice. The Foxboro Dewcel, reported by *Hickes* [1947], is a phase cell that maintains a temperature which ideally would be that of the LiCl dew point of the air surrounding it. Thus a measurement of the Dewcel temperature provides the dew point or absolute humidity of the air in which the Dewcel is placed. A modification of the Foxboro Dewcel is shown in Figure 2. A thermometer bulb is covered with a fiberglas sheath (wick). A bifilar winding around the wick is connected to a 60-cycle voltage source. When the wick is saturated with LiCl solution, the applied voltage causes current conduction in the solution on the wick and this in turn heats the wick and the enclosed thermometer bulb. The temperature of the bulb eventually arrives at the LiCl dew point. A further temperature rise above the LiCl dew point causes the solution to evaporate over to the salt, increases markedly the resistance between the windings, and decreases the power input and heating. If the Dewcel temperature is below the LiCl dew point, water vapor collects on the wick and increases the wick conductivity, which increases power input and heating. At equilibrium there is LiCl salt and sufficient solution on the wick to maintain a power input that satisfies heat losses.

Dewcel use in heat budget measurements—The measurement of the vertical heat budget of a crop requires the measurement of the vapor-pressure gradient over the crop. The gradient is approximated by a change in vapor pressure over a small height interval. This measurement cannot be made precisely by placing Dewcels at different heights above the crop since the absolute difference between Dewcels may be 0.5°C and even greater if ventilation of the Dewcels differs. An arrangement found to be successful is illustrated schematically in Figure 3. The Dewcel was modified for this method to permit thermopile thermometry which was most convenient to an accurate measurement of a small vapor-pressure gradient. Space was also conserved with this Dewcel modification. The Dewcels are kept at constant ventilation and at equal air temperature. In addition, the absolute difference between Dewcels was balanced out.

Air was sampled by two nozzles. The lower nozzle was set 10 to 15 cm above the crop surface and the upper nozzle was spaced vertically 60 cm above the lower nozzle. The air was transported through plastic, $\frac{3}{4}$-inch garden hose to a shelter where the drums, Dewcel chambers, and other apparatus were located. The nozzles were supported on a boom that was rotated back and forth over the crop surface so that there was space integration over a 50- to 60-foot path. Vapor-pressure differences were found to fluctuate considerably over crop surfaces. Since the Dewcels have a shorter time constant on heating than on cooling, suitable integration was provided by placing a 15-gal oil drum which contained a fan for mixing the air in each of the two airstreams ahead of the valve network. These integrated the higher frequency

LiCl DEW POINT, °C	-16.5	0	10	12.5	20	30	40	50	60	70	80	90	100
DEW POINT, °C over WATER	-28.8	-20.8	-16.0	-15.0	-10.1	-3.4	3.4	10.6	17.7	24.6	31.6	38.5	45.3
DEW POINT, °C over ICE	-26.0	-18.5	-14.3	-13.4	-9.0	-3.0	—	—	—	—	—	—	—
VAPOR PRESSURE, mb	0.57	1.17	1.76	1.92	2.84	4.75	7.8	12.8	20.3	30.9	46.7	68.0	97.3
LiCl SALT HYDRATION	Di- + TRI-	DI-HYDRATE		Mono + Di-	MONO-HYDRATE								

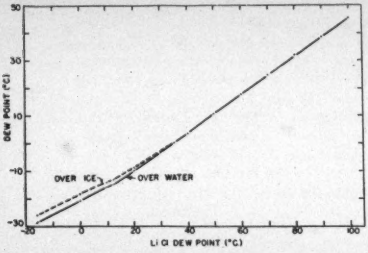

FIG. 1 – Relation between LiCl dew point and dew point over water and ice

fluctuations, and provided a time constant of eight minutes or longer. Measurements every ten minutes provided sufficient information on dew-point differences. The drums were coated with Tygon paint and silicone (DC-4) grease to prevent excessive vapor sorption and release.

The absolute difference between Dewcels was balanced out by switching the valve every ten minutes so that the two air streams were alternated between the two chambers. At the same time the air streams were switched, the polarity of the thermocouple leads to the recorder was switched. Thus, the difference in dew point between the two air streams was an average of the two different readings with the errors in absolute temperature of the Dewcels canceled.

$$\Delta T_{meas} = \Delta T_{true} + \text{error (before reversal)}$$
$$\Delta T_{meas} = \Delta T_{true} - \text{error (after reversal)}$$
$$2\Delta T_{meas} = 2\Delta T_{true} \quad \text{(sum)}$$

Time was allowed after each switch for temperature equilibrium before temperature data was recorded.

The Dewcel apparatus was tested in the field against a proven wet-dry bulb psychrometer arrangement [*Suomi*, 1953] and found to be satisfactory. The advantage of the Dewcel measurement over the psychrometric measurement is the convenience in reducing data and that the per cent error is the same at all dew points. Extremely small vapor-pressure differences can be measured. A vapor-pressure difference of 0.047 mb has been measured between two air streams when the air vapor pressure was 23 mb. This difference, which amounts to two parts in 1000, has been measured with a relative error of two per cent. A typical vapor-pressure gradient measurement over a hay crop on a partly cloudy day is shown in Figure 4, which gives the vapor-pressure difference over a 60-cm height interval.

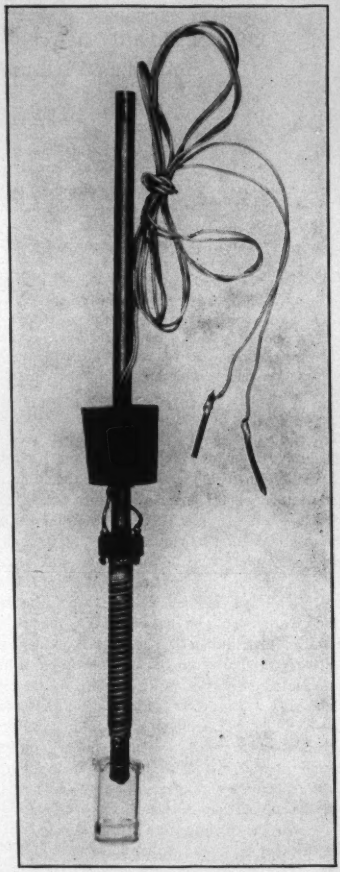

FIG. 2 – Dewcel modified for thermocouple thermometry

Apparatus—The Dewcel modification for temperature measurement with thermocouples is

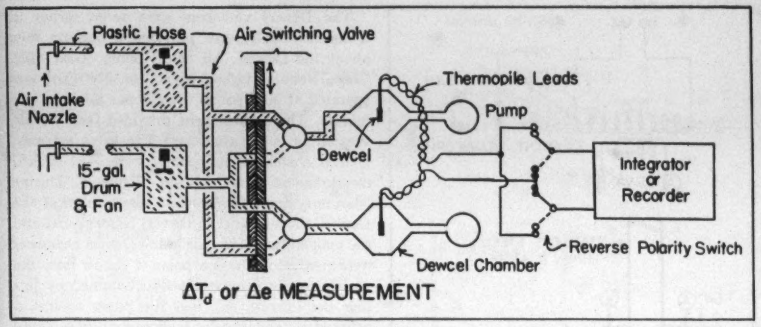

FIG. 3 – Schematic diagram of equipment for dew-point gradient measurement

shown in schematic in Figure 5. In the construction, 18 gage copper wires were cemented into the bakelite (linen) collar with Araldite 551 (Ciba Co.). The bakelite plug and the 0.25 inch OD × 6–10 mil wall stainless steel tube were then cemented to the 0.25 inch ID × 20 mil wall fine silver tube (J. Bishop and Co.) with Araldite 551. The bakelite collar then was cemented in place on the stainless tube. The cementing joints and the silver tube were cleaned and then the bakelite and silver surfaces were coated with two layers of Sylkyd 1400 varnish (Dow Corning Corp.). The two wire binding holes and a $\frac{3}{32}$ inch hole in the bakelite plug were drilled. The $\frac{3}{32}$ inch hole in the plug supported the bale of a small lucite bucket that was placed on later to trap any LiCl solution that may have dropped from the wick and contaminated the Dewcel housing if power failed. The fiberglas sleeve (Silverflex no. 4, natural sleeving, Insulation Manufacturers' Corp., Chicago) was placed on the silver bulb. Two 22-inch lengths of 30 gage (10 mil) fine silver wire was inserted, folded, and wedged into the binding holes. The bi-filar windings were spaced with a jig or lathe at a pitch of six threads per inch to give wire spacings of $\frac{1}{12}$ inch, and soldered at the bakelite collar to the copper binding posts. Fine plastic-insulated antenna wire was soldered to the other end of the binding post for the transformer leads. A rubber stopper was placed over the stainless tube and transformer leads and any gaps were sealed with rubber-base cement. The thermometer bulb was filled with transformer oil for thermal contact to the inserted five-junction thermopile.

Preliminary trials demonstrated that a bi-filar winding on the wick with wires spaced 12 turns per inch and powered with a 25-volt supply was suitable. Much higher voltages tended to promote unstable operation and lower voltages decreased heating response undesirably. If windings were spaced close (for example, 20 turns per inch), the Dewcel became less stable in operation; and if wires were spaced widely (for example, eight turns per inch) there were obvious cool and hot spots on the wick producing a non-uniform bulb temperature. The current density at the windings, when the element was heated to place it into operation, was sufficient to decompose the LiCl electrolytically and produced Li_2CO_3 unless the currents with frequencies of 2000 to 5000 cycles were used. However, the amount of Li_2CO_3 formed under severe conditions was not sufficient to affect operation seriously since appreciable amounts of impurities were required to affect the Dewcel operation. In fact, some silicone oil drenched the wick accidently during one experiment and this decreased the operating temperature from about 47 to 45°C. The 25-watt bulb in the transformer primary was found to be a suitable ballast to limit power input when the Dewcel was placed into operation.

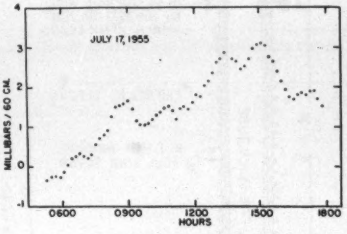

FIG. 4 – Vapor-pressure gradient measurement over hay on a partly cloudy day

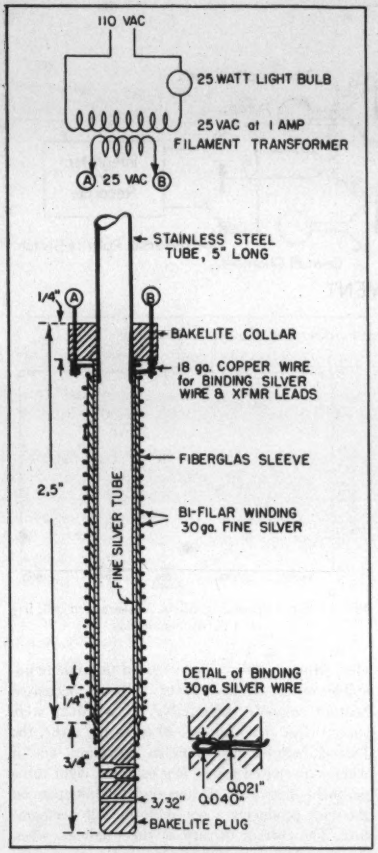

FIG. 5 – Schematic diagram showing Dewcel construction

A vapor-pressure generator shown in the schematic diagram Figure 6 supplied 5 to 22 liters/minute of air at a controlled dew point. The control was as good as the control of the temperature bath. The air from the vapor-pressure generator could be divided and channeled directly to two Dewcel chambers or could be channeled to the chambers through the valve network so that air streams could be alternated between the chambers. The air temperature adjusted to room temperature while passing through the tubing.

The Dewcel chambers were seven inches in diameter. The screens provided a uniform flow about the Dewcel. An oilless pump (Gast Mfg. Corp., Benton Harbor, Mich., no. 0240-101) was operated at 300 rpm to draw about 8.3 liters per minute. The arrangement provided 0.33 m/min ventilation in the chambers. The valve network, Dewcel chambers, and pumps were used in field measurements illustrated in Figure 3. During laboratory tests, the absolute temperature of the Dewcel, the difference in Dewcel temperatures and the temperature of the air in the Dewcel chambers were measured. The dew point of the air from the vapor-pressure generator was determined by jetting the exhaust air from the pump against a polished metal dew-point hygrometer. Presumably the same air could be passed through by a psychrometer in a suitable arrangement. A wet-test flow meter was connected to the pump exhaust to measure the volume of air pumped and the ventilation of the Dewcel.

Dewcel characteristics—The Dewcel is a heat-balance instrument. At an equilibrium temperature, the power input must equal the advection, convection, and radiation heat losses. Since the power input depends upon the wick conductivity and wick conductivity varies with the amount of LiCl solution on the wick, it was expected that the Dewcel temperature would differ from the LiCl dew point as heat loss from the bulb was changed with a change in ventilation or ambient temperatures. Departures of Dewcel temperature from the LiCl dew point would affect the calibration of the Dewcel for precise vapor-pressure difference measurements. Measurements were made to determine the effect of heat losses from the Dewcel upon its operation.

Power requirement of Dewcel—The resistance of a Dewcel element was measured with an ac bridge at various temperatures near the LiCl dew point at which it would operate ideally. This was done by ventilating the Dewcel with air of known dew point and varying the temperature of the air with a heater through a range from below to above LiCl dew point. The results are shown in Figure 7. The points include runs made at LiCl dew points of 35.5, 48.4, and 67.3°C. It is noted that the Dewcel resistance or power input does not change abruptly from low to very high values at the LiCl dew point. Why the resistance remains reasonably low for two to five degrees above the LiCl dew point is not known, though the conductivity of $LiCl \cdot H_2O$ crystals possibly may contribute. It is evident that at a given air dew point, the Dewcel will operate over a range of temperatures depending upon heat

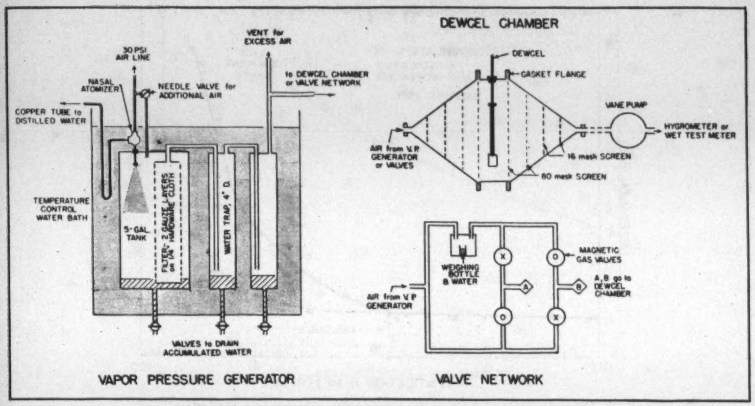

FIG. 6 – Schematic diagram of vapor-pressure generator, the Dewcel chamber, and the air switching valves

losses. The Dewcel operating resistance, which depends upon the heat dissipation, is normally from 1000 to 5000 ohms (about 0.625 to 0.125 watts at 25 vac).

Ventilation effects—The effect of ventilation is shown in Figure 8. The tests were made by placing the test Dewcel in a chamber and a reference Dewcel in a similar chamber, with the same dew point air passed through both chambers. The ventilation of the test Dewcel was varied while the ventilation on the reference Dewcel was held constant. The temperature difference between the two Dewcels was measured to find the temperature depression caused by ventilation. Ventilation in excess of about one meter per minute cooled the Dewcel markedly below its operating temperature. The temperature depression is about proportional to the square root of the ventilation at higher ventilations (region where power input varies little with Dewcel temperature). At higher ventilations the wick is quite wet, the electric conductivity is high, and the Dewcel is unstable. Either small changes of vapor pressure in the ventilation stream, small but rapid changes in ventilation, or changes in voltage supply will cause the Dewcel to overheat, completely drying the wick. As expected, the two ventilation curves indicate that ventilation has less effect as the Dewcel temperature approaches the temperature of the surrounding air. The temperature depression observed when the Dewcel was ventilated with airflow parallel to the Dewcel axis was somewhat less than that observed with ventilation normal to the axis. During the experiment it was noted that the temperature depression was greater when ventilation was increased than when ventilation was decreased. This is caused by hysteresis effects in the woven wick. Such hysteresis is common in porous materials. Because of instability in operation at high ventilation and because of the uncertainty hysteresis creates, operation at low ventilation rates is necessary.

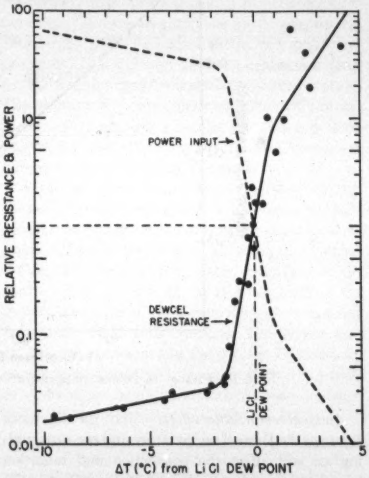

FIG. 7 – Resistance (and power input) of the Dewcel element as a function of Dewcel temperature

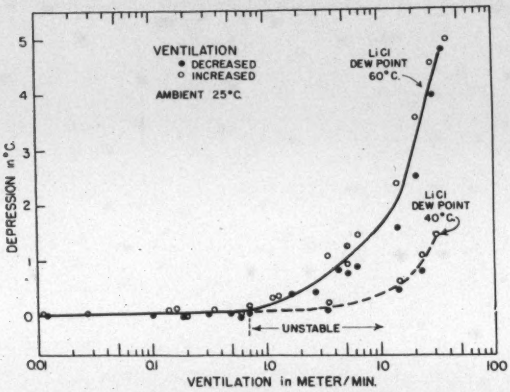

FIG. 8 – Dewcel temperature depression effected by ventilation

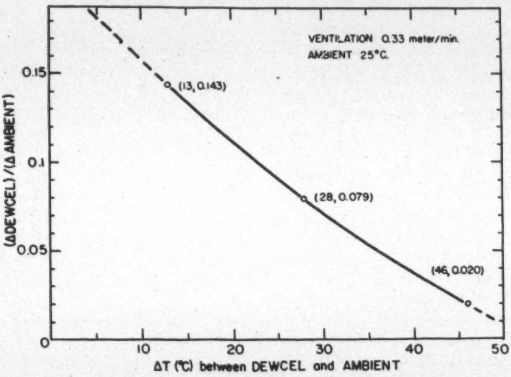

FIG. 9 – Change in Dewcel temperature effected by changes in ambient temperature

Ambient-temperature effects—Since the difference between the Dewcel temperature and the surrounding air will affect the convection and radiation heat losses, ambient air temperatures influence the equilibrium temperature of the Dewcel. If the LiCl dew point is considerably higher than ambient, the Dewcel temperature will be below LiCl dew point. If ambient temperatures are close to the LiCl dew point, the Dewcel temperature will be above the LiCl dew point. In fact, if ambient is above the LiCl dew point, the Dewcel will be above ambient. Thus, even with no forced ventilation, the slope of the dew-point—Dewcel-temperature curve is greater than the dew-point—LiCl dew-point curve of Figure 1. For example, the mean slope of the curve in Figure 1 is 0.697. If the Dewcel is not force ventilated and fairly well shielded from radiation losses, the mean slope of the dew-point — Dewcel-temperature curve is 0.702, and at a forced ventilation of 0.33 m/min, the mean slope is about 0.75. The effect of fluctuations in ambient temperature from 25°C upon the fluctuations in Dewcel temperature is given in Figure 9. These data were obtained in the apparatus used for the ventilation tests except ventilation was held constant and the air temperature of one air stream was varied.

Because of the complex nature of the Dewcel

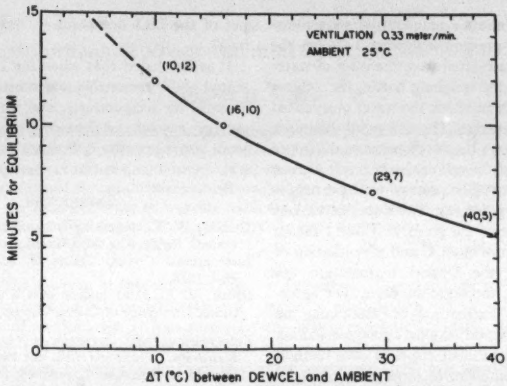

FIG. 10 – Time required for equilibrium as influenced by Dewcel temperature

heating and equilibrium mechanism, the Dewcels are not highly accurate in their absolute readings, particularly when used with thermocouples which may sample hot or cold spots in the Dewcel bulb. Departures of 1 to 1.50°C from the LiCl dew point may be found at a 0.33 m/min ventilation, though departures less than 0.5°C may be achieved with care. Depending upon ventilation and radiation shielding, the Dewcel must be operated 10 to 15°C above ambient to read close to the LiCl dew point. Usually a calibration of the instrument under the conditions at which it is operated is desirable.

Equilibrium times—Because the Dewcel is cooled by ventilation and radiation losses and heated by a power supply, the time constant of cooling is considerably greater than that of heating. Moreover, the Dewcel overshoots on both heating and cooling. The time required to reach equilibrium is decreased with increased ventilation. Because the cooling time constant is larger than the heating time constant, the Dewcel cannot be used easily to integrate dew points that change over periods less than the Dewcel time constant. If ventilation is increased to give equal cooling and heating time constants the Dewcel is so strongly ventilated that it is unstable. Time required for equilibrium is shown in Figure 10.

Calibration—The Dewcel requires calibration in order to measure either a dew point or a difference in dew point between two air streams. Two methods of calibration were used. In the first method, a Dewcel was placed in a chamber to which air from the vapor-pressure generator was channeled at constant ventilation. At various Dewcel temperatures above ambient, the Dewcel temperature was measured and the air dew point was determined with a polished metal dew point hygrometer. This gave an absolute calibration temperature of dew point versus Dewcel temperature. The slope of the curve between given calibration points above ambient provided the (Δdew point)/(ΔDewcel) calibration for determining dew-point differences from Dewcel differences.

A second method consisted of setting up two Dewcel chambers connected to the vapor-pressure generator through the valve network so that a dew-point difference was measured. A small weighing bottle, partially filled with water, was placed in the container in one arm of the system ahead of the valves. The pumps were connected to a wet-test flow meter filled with kerosene. The system was placed into operation and the average Dewcel temperature difference was determined over a period of 10–24 hours. In addition, both the absolute Dew-

TABLE 1 – *Dew-point – Dewcel temperature slopes at various Dewcel temperatures*

Dewcel temp.	Temperatures above ambient	By polished metal dew-point hygrometer	By dew-point — Dewcel differences	Corrected for temperature above ambient
°C	°C			
31 – 37	6 – 12	0.85	...	...
36	11	...	0.80	0.693
38 – 47	13 – 22	0.77	...	0.688
48 – 57	23 – 32	0.76	...	0.700
54	29	...	0.75	0.699
63	38	...	0.72	0.690
64 – 66	39 – 41	0.71	...	0.687

cel temperature, and air temperature were measured. The vapor-pressure difference between the air streams was calculated from the mass of water evaporated from the weighing bottle, the volume (¼ the total) of air in which the water evaporated and the air temperature. The dew-point difference was determined from the vapor-pressure difference to give the slope of the calibration curve at a given Dewcel temperature. The process was repeated for other Dewcel temperatures. The slopes at various Dewcel temperatures are given in Table 1 for an ambient temperature of 25°C and a ventilation of 0.33 m/min. As the Dewcel temperature approaches ambient, the slope increases. The agreement between the two methods of determining the (Δdew point)/(ΔDewcel) slope are good considering that there are independent errors in each method that could contribute two to three per cent maximum error. The slopes were corrected for ambient temperatures from the data given in Figure 9. It is seen that all the corrected slopes are within 1.5 pct of the LiCl dew-point — dew-point slope of 0.697.

It is concluded that when the Dewcels are operated under reasonable and constant ventilation, at equal air temperatures, and with provision for nulling absolute differences between Dewcels, small vapor-pressure differences can be measured with errors less than two to three per cent.

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Type Distributions of Precipitation at Selected Stations in Illinois

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Abstract—All the precipitation which fell during a ten-year period at four first-order weather stations in Illinois is classified according to its source from one of six major types of precipitation systems: (1) cold front; (2) warm front; (3) stationary front; (4) squall line; (5) warm air mass; and (6) cold air mass. The amount of precipitation and the frequency of occurrence for each of the six major types by monthly totals are presented in tabular and graphic form. Squall lines and warm air mass showers are shown to be of much greater importance at Cairo than at the stations farther north.

Introduction—The purpose of this study was to ascertain quantitatively the relative importance of the major types of precipitation at four selected stations in Illinois with respect to their contribution to the total water budget and to their frequency of occurrence.

Sources of data—The U. S. Weather Bureau daily weather maps containing a large scale 00h30m CST and a small scale 12h30m CST surface chart and a small scale 700-mb chart were used as the source for determining the type of precipitation for the years 1944–1953 [U. S. WEATHER BUREAU, 1944–1953]. Hourly precipitation data [U. S. WEATHER BUREAU, 1944–1953] for the U. S. Weather Bureau stations at Chicago, Moline, Springfield, and Cairo were used (Fig. 1).

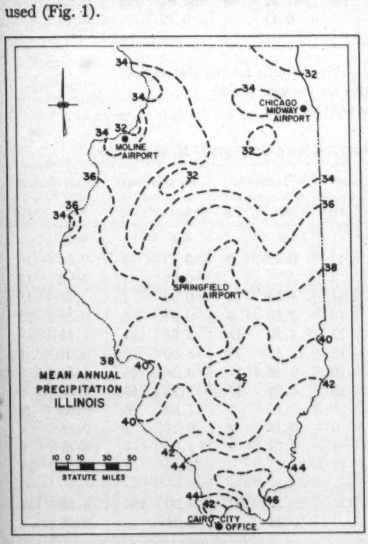

FIG. 1 – Location of stations

Definitions of precipitation types—Each occurrence of precipitation, which was obtained from the hourly precipitation data, was classified into one of the following six types: (1) cold front type, that occurring from one hundred miles in advance of the cold front until the end of precipitation after the frontal passage; precipitation resulting from cold-type occluded fronts was included in this class; (2) warm front type, that associated with the approach and passage of a warm front or warm-type occluded front; (3) stationary front type, that associated with warm air overrunning up the slope of a stationary front or with very weak stable waves on a stationary front to the south of the station; (4) squall line type, that from all types of squall lines; sometimes the term squall zone might have been applied; (5) warm air mass type, that occurring within the warm air mass in the absence of fronts; this includes thermal convection and nocturnal showers; there was usually a trough aloft associated with this type of precipitation; and (6) cold air mass type, that occurring in the cold air mass after the passage of the cold front and distinctly separated from the cold front by a zone without precipitation; most of this is usually termed cold air mass instability showers; however, some cases occurred deep within a large cold air mass and were associated with the passage of a minor trough aloft.

Definition of frequency of occurrence—The following criteria were used to establish the frequency of occurrence of each type of precipitation:

The passage of a cold or warm front was considered as one occurrence without regard to short-period interruptions of one to two hours in the precipitation. If a break of three or more hours in the precipitation occurred, which indicated that the front had passed, then the following precipitation was classified as cold air mass or warm air mass, as applicable.

Stationary front precipitation was considered as one occurrence as long as there were only minor

breaks of one to two hours. If there were major breaks in the precipitation of the order of a half day, which usually resulted from the passage of minor stable waves along the stationary front, then each new outbreak of precipitation was counted as another occurrence of stationary front precipitation.

Squall line precipitation was restricted to those cases in which squall lines were shown on one of the maps and each was counted as one occurrence. Therefore, the frequency of squall lines and their total contribution to the precipitation at each station are perhaps too small. The undetected squall lines were probably classified as warm air mass precipitation in most cases, with a few that were less than one hundred miles in advance of cold fronts being classified as cold front precipitation. If the precipitation records indicated light showers before and after the probable time of the squall line passage, with breaks of one hour or

TABLE 1 - *Type distributions of precipitations by months, 1944–1953, Chicago Midway Airport*

Month	Cold front		Warm front		Stat. front		Squall line		Warm air mass		Cold air mass	
	Amt	Fq	Amt	Fq	Amt	Fq	Amt	Fq	Amt	Fq	Amt	Fq
	inch		inch		inch		inch		inch		inch	
January	5.21	35	10.88	31	2.89	14	0.22	1	0.25	4	0.50	17
February	6.83	36	7.65	33	0.43	3	0.09	1	0.31	5	0.91	21
March	10.98	54	14.10	43	3.75	11	2.27	8	0.59	4	1.70	18
April	14.65	57	12.09	40	2.16	6	4.46	8	0.87	7	1.06	22
May	11.36	39	12.36	30	7.21	21	3.52	12	1.98	12	1.45	14
June	9.35	26	9.26	24	7.20	18	11.01	25	5.99	15	0.22	5
July	6.29	28	2.53	8	3.61	13	11.15	14	9.24	25	1.97	7
August	11.08	33	3.70	10	4.34	14	3.34	11	3.76	11	0.20	4
September	10.53	33	8.19	12	2.92	11	2.23	6	2.06	16	1.43	14
October	8.12	23	4.58	13	1.46	8	0.99	4	0.96	6	0.76	10
November	7.79	43	7.57	23	1.14	4	1.79	7	3.32	9	1.06	23
December	11.17	36	11.63	32	1.89	7	0.29	1	0.71	6	1.19	20
Totals	113.36	443	104.54	299	38.76	130	41.36	98	30.04	120	12.45	175
Averages	0.27	...	0.35	...	0.30	...	0.42	...	0.25	...	0.07	...

Stat.—Stationary.
Amt—Total amount of precipitation in inches for respective months for ten-year period.
Fq—Total number of occurrences for respective months for ten-year period.
Averages—Average contribution in inches per occurrence.

TABLE 2 - *Type distributions of precipitation by months, 1944–1953, Moline Airport*

Month	Cold front		Warm front		Stat. front		Squall line		Warm air mass		Cold air mass	
	Amt	Fq	Amt	Fq	Amt	Fq	Amt	Fq	Amt	Fq	Amt	Fq
	inch		inch		inch		inch		inch		inch	
January	5.02	30	8.76	28	1.89	12	0.33	1	0.27	2	0.53	10
February	4.85	28	9.25	28	0.27	3	...	...	0.06	2	0.90	13
March	9.69	46	14.58	42	5.49	14	1.65	5	0.39	2	1.61	15
April	13.75	45	12.80	36	2.35	10	2.80	8	0.31	5	0.55	13
May	8.11	40	11.03	28	9.90	27	1.29	11	3.83	11	1.15	17
June	5.88	24	14.58	27	8.01	18	17.62	29	5.60	21	0.01	1
July	10.16	26	4.16	8	3.74	10	9.40	17	9.26	25	1.51	5
August	10.05	32	11.20	14	2.50	10	6.29	17	5.15	13	0.36	5
September	14.72	28	6.38	15	3.17	9	3.75	7	1.80	10	0.66	9
October	5.32	19	5.70	11	1.75	9	0.39	2	0.21	3	0.35	6
November	6.30	33	6.28	19	0.96	4	2.73	5	1.96	9	0.40	9
December	6.47	25	7.96	35	2.65	11	...	...	0.06	1	0.53	11
Totals	100.32	376	112.68	291	42.68	137	46.25	102	28.90	104	8.56	114
Averages	0.27	...	0.39	...	0.31	...	0.45	...	0.28	...	0.08	...

See note at end of Table 1 for meaning of abbreviations.

more separating the shower precipitation from the squall line, then the showers were counted as an occurrence of warm air mass precipitation separate from the squall line. If the precipitation remained continuous for several hours with the passage of a squall line, it was counted as one occurrence of a squall line only.

The frequency of warm and cold air mass precipitation can be considered primarily as shower days or half days because no attempt was made to classify showers separated by one-hour intervals as separate occurrences. Usually the warm or cold air mass showers persisted for about four to six hours with only minor breaks during the period as shown by the precipitation records. If there were distinct shower periods separated by several hours, then each shower period was counted as a separate occurrence.

Interpretations of findings—Tables 1–4 give the ten-year totals of each type of precipitation by months at the respective stations. These tables also show the average contributions in inches per occurrence of each type of precipitation. Tables 1–4 reveal two important features:

(1) A winter and spring maximum in the amount of both cold front and warm front pre-

TABLE 3 – *Type distributions of precipitation by months, 1944–1953, Springfield Airport*

Month	Cold front		Warm front		Stat. front		Squall line		Warm air mass		Cold air mass	
	Amt	Fq	Amt	Fq	Amt	Fq	Amt	Fq	Amt	Fq	Amt	Fq
	inch		inch		inch		inch		inch		inch	
January	6.61	29	9.40	36	3.98	14	0.05	1	0.39	7	0.25	15
February	6.06	35	9.80	32	3.02	10	...	...	0.43	3	1.56	15
March	7.37	41	16.41	43	5.68	17	3.29	10	0.55	6	1.14	21
April	13.33	48	15.11	30	3.01	13	2.09	10	3.60	9	0.66	14
May	8.87	42	6.66	20	4.70	21	9.05	18	2.65	12	1.71	20
June	7.82	23	7.76	23	8.29	14	15.62	34	9.89	27	0.39	6
July	4.91	15	6.38	8	5.71	12	6.82	20	7.74	28	0.68	4
August	8.81	22	5.13	11	3.78	9	3.39	13	2.80	12	0.10	4
September	8.26	33	7.93	10	3.27	9	4.66	9	4.77	18	0.41	4
October	11.43	24	3.98	11	4.61	13	1.35	6	2.26	10	0.37	8
November	7.92	38	8.18	24	1.63	5	0.79	5	1.97	11	0.35	13
December	4.59	30	9.36	29	5.40	9	0.50	1	0.52	6	0.24	9
Totals	95.98	380	106.10	277	53.08	146	47.61	127	37.57	149	7.86	133
Averages	0.25	...	0.38	...	0.36	...	0.37	...	0.25	...	0.06	...

See note at end of Table 1 for meaning of abbreviations.

TABLE 4 – *Type distributions of precipitations by months, 1944–1953, Cairo City Office*

Month	Cold front		Warm front		Stat. front		Squall line		Warm air mass		Cold air mass	
	Amt	Fq	Amt	Fq	Amt	Fq	Amt	Fq	Amt	Fq	Amt	Fq
	inch		inch		inch		inch		inch		inch	
January	19.11	46	21.88	34	7.25	20	4.52	3	3.83	16	0.24	12
February	14.22	38	20.55	34	6.10	11	2.16	4	4.52	14	0.18	5
March	16.20	48	18.58	36	8.09	13	6.93	11	4.87	9	0.41	15
April	10.82	35	13.83	27	4.53	14	11.44	18	3.43	13	0.62	10
May	11.58	35	5.51	16	7.62	22	17.27	30	5.73	18	0.67	9
June	10.29	24	1.54	4	5.47	11	12.74	28	18.08	47	0.71	1
July	4.91	18	1.42	4	4.59	10	9.57	17	7.19	37	0.32	6
August	9.60	13	1.33	6	4.26	14	4.58	12	15.32	25	0.49	5
September	10.73	23	3.43	7	2.41	10	5.01	8	9.26	31	0.49	9
October	7.46	25	2.91	6	2.00	10	4.26	4	8.21	18	0.23	3
November	14.95	40	10.03	24	8.32	10	6.68	8	3.70	13	0.27	8
December	7.83	36	19.27	32	6.36	12	3.54	4	4.62	14	0.14	5
Totals	137.70	381	120.28	230	67.00	157	88.70	147	88.76	255	4.77	88
Averages	0.36	...	0.52	...	0.43	...	0.60	...	0.35	...	0.05	...

See note at end of Table 1 for meaning of abbreviations.

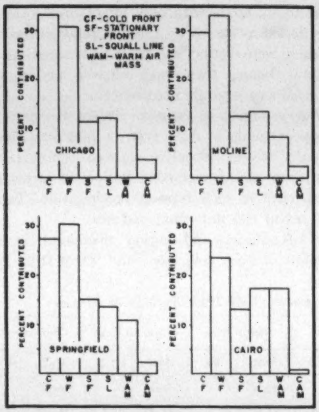

FIG. 2 – Per cent of total precipitation for ten-year period contributed by each type of precipitation

cipitation occurred at Cairo, whereas at the other three stations there were two maxima of cold front precipitation, one in the spring, and one in the late summer and early autumn, and one maximum of warm front precipitation in the spring.

(2) The average contribution per occurrence of cold front type precipitation was greatest in late spring and early autumn at all four stations. This condition was most pronounced at the stations farthest north. The number of precipitating cold fronts per month in winter or early spring was nearly twice the number per month in late spring or early autumn. However, the average amount of precipitation contributed by the winter and early spring cold fronts was just about 60 pct of that contributed by the cold fronts of late spring and early autumn.

The data were also tabulated by amounts and frequencies of occurrence of each type of precipitation for each year. This tabulation indicated that the ten-year period chosen for study had approximately normal distributions of frequencies and amounts of precipitation for each of the six types of precipitation.

Comparisons between stations—Warm air mass showers and squall lines are relatively more important at Cairo than at the other three stations (Fig. 2). At Chicago, Moline, and Springfield, cold and warm fronts stand out in their percentage contributions of precipitation. Also interesting is the high relative importance of cold air mass precipitation at Chicago compared to Cairo. One reason for this is that Lake Michigan acts as a source of heat and moisture at Chicago during autumn and early winter.

The average contributions in inches per occurrence of the different precipitation types are practically in identical order of rank at all four stations, Tables 1–4: squall lines, warm fronts, stationary fronts, cold fronts, warm air mass showers, and cold air mass showers. Squall lines ranked first in average contribution per occurrence, probably because they are made up of thunderstorms which have high rainfall rates. It is worthy of note that warm fronts and stationary fronts averaged higher amounts of precipitation per occurrence than cold fronts at all four stations. The probable explanation for this lies in the persistent nature of warm and stationary fronts in winter.

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Effect of Ship's Roll on the Ekman Current Meter

SUSUMU TABATA AND A. W. GROLL

Abstract—Tests were made with a pair of Ekman current meters to observe the effect of ship's roll upon their measurements and their behavior. In calm seaways where the current speed ranged from five to 45 cm/sec the speeds indicated by the two instruments were consistent within five per cent, and the indicated directions were within four degrees. In weaker currents the direction difference is twice as large. When the sea/swell conditions became greater than 1/1 the scatter in the indicated speeds became greater than ten per cent, and the results were considered unusable. Directions were measured within an accuracy of ten degrees in sea/swell as great as 2/3. One instrument was given an oscillation approximating a movement caused by a ship's roll of 10 to 15°. Its recorded speeds were 1.5 times those measured by a stationary one. This increase is due to the excess revolutions made by the propeller of the oscillating instrument during its downward swing. The increase in the scatter of the speed differences of the two instruments during sea/swell >1/1 is attributed to this also. There was no appreciable variation in the directions during this artificial roll except when measurements were made in weak currents.

Introduction—The Ekman current meter is widely used to observe ocean currents because of its relatively low cost, its simplicity and ruggedness of construction, and the reliability of its measurements when used in calm seas. The Pacific Oceanographic Group has used this instrument extensively in the study of the coastal currents of British Columbia. However, from time to time measurements have been made from anchored ships that rolled in the seaway. Under such conditions the measurements obtained were considered doubtful.

Since the effect of the ship's roll upon these measurements and also upon the behavior of the instrument was not too well known, series of tests were made to observe this. These tests were made by employing a pair of Ekman current meters in the following experiments: (1) simultaneous measurements from a rolling ship in a rough seaway; (2) simultaneous measurements from a steady ship in a calm seaway; (3) simultaneous measurements during an artificial ship's roll in which one instrument was given an oscillation simulating a motion caused by a ship's roll while the other was kept stationary; and (4) direct underwater observation of the behavior of the instruments during Experiment (3).

The Ekman current meter was designed by *Ekman* [1905] and has since been improved [1932]. The instrument records the number of revolutions made by an eight-blade propeller during an arbitrary time interval. A calibration curve is used to relate these data to the current speed. The current directions are indicated by small metal balls which are released at intervals and are directed by a magnetic compass into one or more of the 36 individual compartments in a radially divided compass box. During measurements, the instrument is lowered over the side of the ship from a wire line whose end is fastened to a swivel mounted on its top, so that it can swing freely about its vertical axis. A lead weight suspended a few meters below the instrument keeps it steady and upright. It is started and stopped by a trigger mechanism that is actuated by the impacts made by the messenger weights despatched along the wire which suspends it.

The ship used for the tests was the Royal Canadian Naval Research Vessel, HMCS *Cedarwood*, a wooden ship of length 51 m (167 ft), beam 9.2 m (30 ft) and draft 4.5 m (15 ft). She has a natural rolling period of 4.5 sec. The booms from which the instruments were suspended were located slightly forward of amidship and 5.5 m (18 ft) outboard of the centerline. Observations were made while the ship was anchored from the bow with the scope (ratio of length of anchor cable out to depth) as small as practicable to reduce ship movement.

In the analysis of the data, no attempt is made to account for the possible deviations in the compass headings of the instruments caused by the magnetism of the ship, as these were considered negligible.

Experiment (1), Simultaneous measurements from a rolling ship—The first test of the series was conducted in a rough sea to compare the measurements obtained by the two instruments under variable rolls of the ship. It was carried out during a routine current survey in Hecate Strait at locations where the depths were greater than 80 m. During this test the sea/swell condi-

TABLE 1 – *The Beaufort scale*

Beaufort scale	Wave height
	ft
0	0
1	Less than 1
2	1 to 3
3	3 to 5

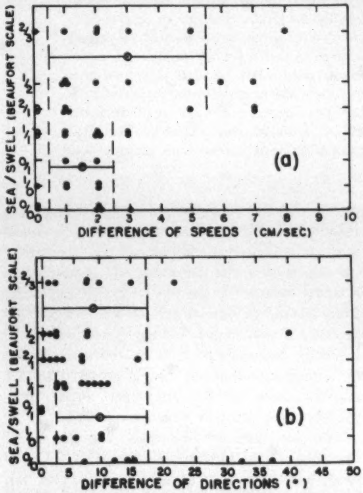

FIG. 1 – Relation between sea/swell conditions and the differences of (a) speeds and (b) directions of the two Ekman current meters; dashed lines are those limits set by ± standard deviations

tions varied from 0/0 to 2/3 on the Beaufort scale (see Table 1) creating a roll up to 20°. The two instruments were suspended on the opposite sides of the ship. They were placed at depths between 10 and 50 m and were allowed to run for periods of two or three minutes.

Figure 1 shows the relationship of the differences of (a) the speeds and (b) the directions of the two instruments with various sea/swell conditions. The observed speeds ranged from 15 to 55 cm/sec with an average of 30 cm/sec. Analysis of the data showed that there was no correlation of the differences with current speed. The apparent error at low speeds was no greater than at high speeds; hence the difference is assumed to be a function of oscillation alone. The difference of the recorded speeds doubled from 1.5 to 3.0 cm/sec when the sea/swell increased from $\leq 1/1$ to $>1/1$ and was accompanied by a proportional increase in the scatter. There was, however, no appreciable change in the differences of recorded directions with sea/swell conditions. These differences were generally within ten degrees during sea/swell from 0/0 to 2/3.

Experiment (2), Simultaneous measurements from a steady ship—This test was made to determine the limits of the reliability of the instruments. During this and the succeeding experiments, the ship was anchored in 70 m; the sea was calm. The two instruments were suspended from the two booms on the same side of the ship with a fore-and-aft separation of about 1.5 m, which was sufficient to eliminate interaction between their compass magnets. The current flowed obliquely to the length of the ship so that one meter was not in the stream of the other. They were lowered to ten meters and, as before, allowed to run for periods of two or three minutes.

The differences between the recorded speeds increased with increasing current speeds as shown in Figure 2. These differences, which amounted to five per cent, were approximately proportional to the recorded speed. The differences in directions were generally within four degrees, but in weak currents they reached values as large as ten degrees.

Experiment 3, Simultaneous measurements during an artificial roll of the ship—This test was conducted to determine the effect of an artificial roll of 10° to 15° of the ship on the meter readings.

One instrument was held stationary at a depth of seven meters while the moving one was placed so that it oscillated about the seven meters depth. The instruments were allowed to run for periods of two or three minutes. In order to simulate the ship's roll of 10° to 15°, it was necessary to give the moving instrument a vertical displacement of 1.8 to 2.8 m and a horizontal displacement of 0.2 to 0.4 m. In practice, however, it was given a vertical displacement of about two meters by one observer working the winch and a horizontal displacement of about 0.5 m by another observer pushing the wire back and forth from the platform (chains). The periods of these oscillations varied from 4.2 to 4.8 sec. The method used here in creating the motion caused by an artificial roll may not be an accurate reproduction of the ship's roll in the sea where irregular rolling occurs, but it is assumed that it can be used to first approximation.

Table 2 shows the speeds and directions recorded by the stationary and oscillating instruments. Observations made when the current

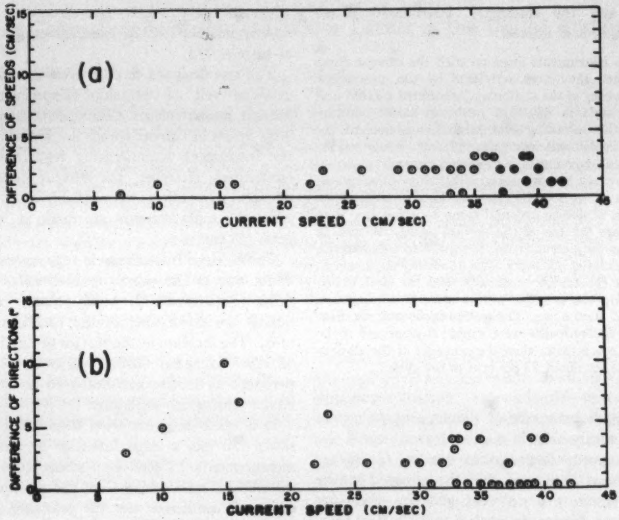

FIG. 2 – Differences of current (a) speeds and (b) directions between the two Ekman current meters placed at a depth of ten meters and observed from a steady ship

TABLE 2 – *Current speeds and directions recorded by moving and stationary Ekman current meters; current speeds greater than 20 cm/sec*

Trials	Stationary speed	Instrument direction	Moving speed	Instrument direction	Differences	
					Speed	Direction
	cm/sec	°	cm/sec	°	cm/sec	°
1	28	280	44	286	16	+6
2	28	276	44	274	16	−2
3	25	276	37	274	12	−2
4	30	278	44	274	14	−4
5	26	274	43	279	17	−5
6	29	270	42	269	13	−1
7	24	274	40	278	16	+4
8	24	279	39	272	15	−7
9	22	284	34	280	12	−4
10	29	274	50	273	21	−1
Mean	26	276	42	276	15	|4|

speeds ranged from 20 to 30 cm/sec (recorded by stationary instrument) demonstrated that the oscillating instrument recorded speeds that were greater than 1.5 times those of the stationary one. There was, however, no appreciable difference in the direction; in fact, the mean difference

TABLE 3 – *Current speeds and directions recorded by moving and stationary Ekman current meters; current speeds less than 10 cm/sec*

Trials	Stationary speed	Instrument direction	Moving speed	Instrument direction
	cm/sec	°	cm/sec	°
1	10	296	11	326
2	5	...	3	326
3	6	336	20	121
4	9	356	20	114
5	5	016	13	043
6	8	016	8	016
Mean	7	...	12	...

only amounted to four degrees. When the currents were weaker (<10 cm/sec) the recorded speed of the oscillating instrument was again much larger, but in this case wide variations in directions occurred, as shown in Table 3.

Experiment (*4*), *Direct underwater observations of the behavior of instruments during Experiment* (*3*)—Direct underwater observations of the instruments during Experiment 3 were accomplished by a team of aqualung divers who examined the action and behavior of both the oscil-

lating and the stationary instruments. Their description is of interest:

"Both instruments lined up with the current directions when they were activiated by the messengers. The propeller of the stationary instrument rotated unit formly, and its direction remained fairly constanduring the recording intervals. The action of the moving instrument was quite different. While making its vertical movements it oscillated through an arc of approximately five degrees on either side of the current direction indicated by the stationary one. When ascending it decelerated and came to a full stop ½ to ¾ m before the top of the upward swing. As soon as the downswing commenced, it started to rotate again, and accelerated markedly. The accelerations, however, were not constant; occasionally near the start of the downswing the propeller would start to rotate, then stop, and start again. The accelerations and decelerations of the propeller were rapid. It appeared to be rotating much faster than the propeller of the stationary meter for about 75 per cent of the cycle."

Discussion—Simultaneous current measurements made by a pair of Ekman current meters from a steady ship in a calm seaway where the current speeds ranged from five to 45 cm/sec (Experiment 2) showed that the recorded speeds agreed within five per cent and the directions within four degrees. In weaker currents (less than 15 cm/sec) the disagreement in directions was about twice as large. These limits define the reliability of the instruments.

During sea/swell $\leq 1/1$ when the ship's roll was small (Experiment 1) the differences in the recorded speeds were the same as those measured from a steady ship whereas the differences in directions were about twice as large (ten degrees compared to four degrees). However, as soon as sea/swell of 1/2 or 2/1 was reached, accompanied by an increase in the ship's roll, the disagreements in speed doubled from five to ten per cent while those of the directions remained unchanged. The implication here is that the random behavior of the instruments causes these variations that increase with increasing sea/swell conditions. It is likely that the recorded speeds are trustworthy when sea/swell conditions are $\leq 1/1$ but too high when they are $>1/1$. The directions, however, appear reliable (within ten degrees) to sea/swell as large as 2/3.

The test designed to determine the effect of an artificial roll of the ship (Experiment 3) on current measurements clearly demonstrated that large errors in current speeds are introduced when the instrument is undergoing regular and rapid oscillations. However, the current directions do not seem to be affected appreciably except perhaps when the measurements are made in weak currents (10 cm/sec).

These large variations in the speed are no doubt due to the erratic revolutions of the propeller (Experiment 4), which rotates excessively during the downswing of the oscillating instrument. The increase in the scatter of the differences of recorded speed during sea/swell $>1/1$ (Experiment 1) is also attributed to its erratic behavior during its oscillation.

It is quite apparent from these tests that the ship's roll has a large influence on the current measurements. Therefore, when currents are measured from a rolling ship, the recorded speeds under all conditions and the recorded directions for weak currents are questionable.

Acknowledgments—Acknowledgments are made to E. B. Bennett, L. H. McCracken, J. E. H. Legare, and to the officers and men of HMCS *Cedarwood* for their assistance during the observations.

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Long-Term Trends of Ground-Water Levels in the United States

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Abstract—Ground-water levels at the end of 1954 were at or near record-low stages throughout most of the southern two-thirds of the United States. These low stages, like those of the early 1930's, have led to frequent expression of the opinion that the water table throughout the country is continuously falling and that we are gradually exhausting our ground-water supplies. A good record of changes in ground-water levels is being obtained by the United States Geological Survey and cooperating State agencies from periodical measurements of water levels in nearly 20,000 observation wells. The records of some of these wells extend back 50 years. Many records are available for the period beginning in 1934. These long-term records indicate that in some areas the ground-water supply is overdeveloped. In the great majority of areas, however, the stage of the water levels correlates with the precipitation. Much of the country has been in drought and the water levels are at a low stage. As the precipitation increases, as it is bound to do later, the water levels will return to higher stages.

Introduction—Ground-water levels at the end of 1954 were at or near record-low stages throughout most of the southern two-thirds of the United States. This low stage of the water table has caused considerable apprehension that our ground-water resources are rapidly being depleted.

In local areas in the United States the available supply of ground water is overdeveloped. These areas include some of the most important aquifers. As an example, the Coastal Plain in Los Angeles and Orange Counties, Calif., where water is pumped from alluvial sand and gravel, is one of the most heavily developed ground-water areas in the United States, and parts of it are seriously overdeveloped. In the High Plains of Texas south of Amarillo, irrigation from wells has been expanding in recent years at a rate greater than in any other comparable area in the United States, and the pumpage so far exceeds the recharge that it is only a question of time until the stored water will be depleted. Ground-water problems of the most serious kind exist in most of the irrigated areas in Arizona, in which State the economy depends to a large extent on irrigation. In 1953 nearly 6,000 irrigation wells were in use in Arizona, not including wells equipped with pumps requiring five horsepower or less [*Halpenny* and others, 1954]. The total pumpage for irrigation in the State in 1953 was slightly more than 4.8 million acre feet. This quantity was about a million acre feet greater than in 1952. The large use of water for irrigation in Arizona has caused a considerable decline of the ground-water level in parts of the State. Figure 1 shows the hydrograph of well D6-6-25ddd in Pinal County, Ariz., for the period 1940 to 1954. From 1940 to 1946 the water level declined about ten feet, but since 1946, concurrently with a large increase in pumping for irrigation, the water level has declined 60 feet and is now about 70 feet lower than in 1940.

The use of water by Wichita, Kans., also demonstrates the great increase in the use of water and the decline of water levels caused by pumping. In 1940 the city began pumping water from wells in the 'Equus beds' about 25 miles northwest of the city. At that time the city was using an average of about ten million gallons a day. In 1954, the average use of water had increased 240 pct to an average of about 34 million gallons a day. This large use of water has naturally caused a considerable decline of the water table in the well-field area. This decline is shown by the hydrograph of well 886 in Figure 1. From 1940 to 1954 the water level in this well declined about 26 ft. This decline represents the removal of a large volume of water, but it seems small in comparison with the total thickness of Pleistocene water-bearing deposits shown by the cross section in Figure 2.

During the past century, the use of water in the United States has increased tremendously. In 1900 the use of water was less than 100 gallons a day per capita, but in 1950 the daily per-capita use of water was more than 1000 gallons. In the half century from 1900 to 1950 the population increased from about 93 million to about 165 million. Our population is increasing at a rapid rate, but our per-capita use of water is increasing at a greater rate.

The Kansas Water Fact Finding Committee reported that in 1954 the farmers in one eastern Kansas county paid, as a result of the drought, $1,000,000 for hauling water for stock and domestic use [*Foley* and others, 1955, p. 112]. The cost of hauling water for stock and domestic use in the

entire State of Kansas in 1954 was more than $7,000,000.

Because of the large increase in the use of water and the shortage of water supplies in many parts of the United States, it is no wonder that the public believes that the water table is declining and that our ground-water supply is rapidly being depleted. It would seem timely, therefore, to review the available facts.

The U. S. Geological Survey and cooperating Federal, State, and local agencies maintain observation wells in every State. At the beginning of 1955 about 20,000 wells were being observed. The water levels in these wells are periodically measured and most of the records are published by the Geological Survey in its annual series of water-supply papers entitled 'Water Levels and Artesian Pressures in Observation Wells in the United States.' Most of the other water-level records are published in project reports by the Geological Survey or by its cooperating State agencies. Records for some observation wells cover a period of half a century. Many wells were started as observation wells during the drought years of the thirties. Because of the many water-level measurements that are available, we are now able to determine whether our ground-water supplies are rapidly being depleted and whether there are long-term trends or changes in the water table.

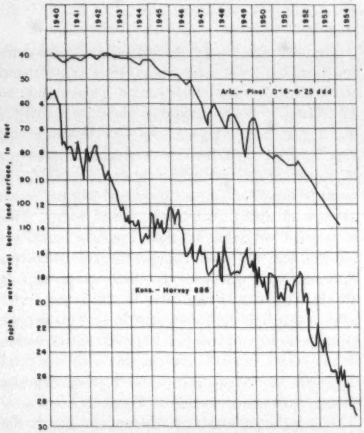

FIG. 1 – Hydrographs of Well D6-6-25ddd in Pinal County, Arizona, and Well 886 in Harvey County, Kans.

A study has been made of the water-level records in local areas in nine States in which records are available for periods of 20 to 50 years. In those particular areas the water table has been affected little, if any, by pumping. Thus, the water levels reflect primarily the natural fluctuations caused by periodical recharge from precipitation and continuous natural discharge; hence, they furnish a good index of the long-term trends of the water table in the United States. The study shows that, in general, the water levels rise during periods of high precipitation and decline during periods of drought.

New York—Regular measurements of observation wells were started on Long Island, N. Y., about 50 years ago. The fluctuations of the water levels in these wells have been summarized by *Jacob* [1945] and by *Luscynski* and *Johnson* [1951]. The records of five wells in Nassau County are summarized in Table 1. In four of these wells the water levels were higher at the end of 1954 than they were at the end of 1913. The highest water level during the period of record in three of the wells was during the last three years. The hydrograph of one of the Nassau County wells is shown in Figure 3. At the end of 1954 the water level in well N-1256 was only a tenth of a foot higher than at the end of 1913, but it was 6.3 feet higher than at the end of 1932.

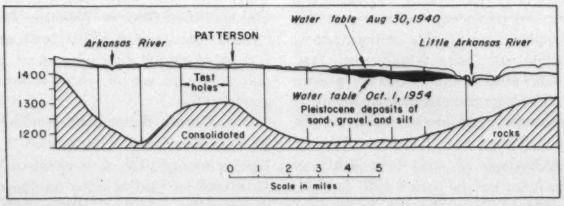

FIG. 2 – Cross section of the Wichita, Kans., well-field area showing the decline of the water table from Aug. 30, 1940, to Oct. 1, 1954

TABLE 1 – *Altitude of water levels in five wells in Nassau County, and average of 14 wells in Nassau and Suffolk Counties, Long Island, N. Y.; water levels are given in feet above mean sea level*

Well	End of year							Highest water level	Year	Lowest water level	Year
	1903	1913	1918	1932	1934	1945	1954				
N1255	..	61.6	58.6	..	60.8	60.9	59.6	65.4	1939	57.7	1954
N1256	..	76.8	71.6	70.6	..	77.6	76.9	80.9	1939	70.3	1933
N1259	..	51.3	..	47.9	..	51.7	53.8	56.8	1952	47.8	1933
N1260	21.0	17.6	..	19.5	..	22.0	22.1	23.6	1953	16.5	1916
N1263	..	49.6	..	46.5	..	50.5	52.1	55.2	1952	46.3	1932
Average of 14 wells		46.5	44.4	43.2	46.3	47.0	47.6	51.0	1939	43.0	1932

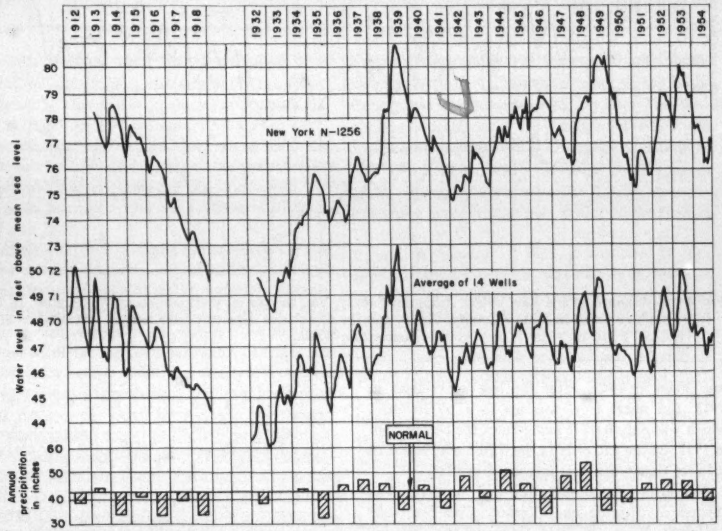

FIG. 3 – Hydrograph of Well N-1256 in Nassau County, N. Y., hydrograph of the average water level in 14 selected wells in Nassau and Suffolk Counties, and the annual precipitation at the Battery, New York, N. Y.

The Geological Survey district office in New York maintains a current average of the water levels in 14 wells in Nassau and Suffolk Counties as an index of the natural changes in the water table in that area. The hydrograph of the average water level in the 14 selected wells is shown in Figure 3. The average water level was 1.1 ft higher at the end of 1954 than at the end of 1913. The highest water level during the period of record (51.0 feet) was in 1939 and the lowest (43.0) was in 1932.

Virginia—A 27-year record of water-level measurements is available for the Ross well in Rosslyn, Arlington County, Va., just across the Potomac River from the District of Columbia [*Meinzer* and *Wenzel*, 1937, p. 480]. A hydrograph of this well is shown in Figure 4. The lowest level during the period of record (25.42 ft below measuring point) was in 1931. The highest water level (15.85) was in 1933. In 1952 the water level was up to 16.49 ft, but, because of the drought during 1953 and 1954, the water level was down to 25.08 ft by the end of 1954. Thus, by the end of 1954 the water level was only 0.34 foot higher than the record low in 1931.

North Carolina—An observation well was started near High Point in Guilford County, N. C., in 1934 [*Meinzer* and *Wenzel*, 1937, p. 217]. Records have been collected on this well since 1934. A hydrograph for this well is shown in Figure 5. The highest water level during the 20-year period of record was 23.92 ft in 1937. The lowest water level

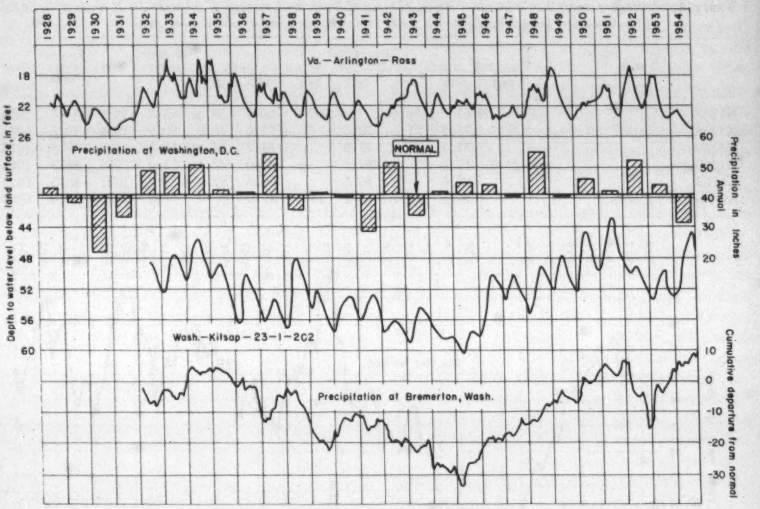

FIG. 4 – Hydrograph of the Ross well in Arlington County, Va., the annual precipitation at Washington, D. C., hydrograph of a well in Kitsap County, Wash., and the cumulative departure from normal precipitation at Bremerton, Wash.

was 30.06 in 1942. After the low water level in 1942, the water level was up to 23.97 in 1953, which was only 0.05 ft lower than the record high in 1937. At the end of 1954 the water level was 0.18 ft lower than when first measured in 1934.

Wisconsin—An observation-well program was started in Monroe and Vernon Counties near LaCrosse, Wisc., in 1934 [*Meinzer* and *Wenzel*, 1937, p. 505]. Seven wells were still being measured at the end of 1954, and the records of all the wells have been published in the annual series of water-supply papers. Well 2 in Monroe County has been selected as typical of the seven wells and its hydrograph is shown in Figure 5. The lowest stage of the water level during the 21-year period of record was in 1935 and was 18.6 ft below the surface. The highest level was in 1952 and was 5.1 ft. At the end of 1954 the water level was 9.0 ft below the surface and 9.6 ft above the low level of 1935.

Iowa—An observation-well program was started in the Tarkio Creek valley in Page and Montgomery Counties, Iowa, in 1934 [*Meinzer* and *Wenzel*, 1937, p. 55]. Measurements were started on 15 wells in the two counties and were still being made on

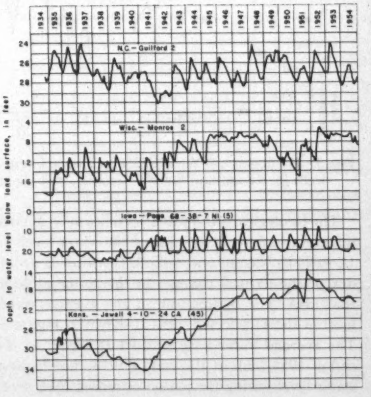

FIG. 5 – Hydrographs for the period 1934 to 1954 for (1) Well 2 in Guilford County, N. C., (2) Well 2 in Monroe County, Wisc., (3) Well 68-38-7N1 in Page County, Iowa, and (4) Well 4-10-24ca in Jewell County, Kans.

TABLE 2 – *Depth to water level in wells measured by Nettleton in 1890 and in nearby wells measured since 1940 and published in Kansas Geological Survey bulletins*

Nettleton Well	County	Location	Depth to water level in 1890	K.G.S. Bull.	Depth about 1940
			ft		*ft*
124	Stafford	SW ¼ sec. 33, T. 23 S., R. 13 W.	16	88	20
133	Barton	NE¼NE¼ sec. 16, T. 20 S., R. 13 W.	21	88	18
137	Barton	SE¼ sec. 8, T. 18 S., R. 13 W.	15	88	15
160	Ford	SE¼NE¼ sec. 5, T. 29 S., R. 25 W.	120	43	125
181	Finney	SE¼SE¼ sec. 12, T. 22 S., R. 33 W.	30	55	25
184	Scott	NE¼NE¼ sec. 25, T. 20 S., R. 33 W.	28	66	31
185	Scott	SE¼ sec. 25, T. 19 S., R. 33 W.	28	66	42
		Average	37		39

five wells through 1954. The hydrograph of a typical well (68-38-7N1, formerly Well 5) is shown in Figure 5. This well is in glacial drift and has a depth of 44 ft. In 1934 the water level was 15.3 feet below the land surface. At the end of 1954 the water level was 15.55 feet below the surface. The highest water level during the period of record was 1.44 ft in June 1947 and the lowest was 19.44 ft in March 1938.

Kansas—In 1890 *Nettleton* [1892] made a study of the artesian pressure and underflow of ground water in several western states, including Kansas. Records were collected on several hundred wells. Later measurements of the depth to water level are not available for the same wells, but they are available for nearby wells from which it is possible to approximate the change in water level since 1890. Seven wells listed by Nettleton in western Kansas are near some wells that have been observed during the past 15 years. The measurements for these wells are given in Table 2. The water levels averaged approximately two ft higher in 1940 than in 1890. This amount [2 ft] is less than the annual fluctuation in some of these wells. The water levels were at a low stage in 1940 because of the drought from 1934 to 1939. It seems probable that the water levels in 1890 were lower than in 1951; but a little higher than at the end of 1954.

During the years 1910 to about 1920, George S. Knapp, later Chief Engineer, Division of Water Resources, Kansas State Board of Agriculture, was stationed at the Garden City Experiment Station. While stationed at Garden City, Knapp made measurements of the depth to water level in many wells in southwestern Kansas, including the well at the Experiment Station and several in Scott County that have been remeasured in recent years. The irrigation well at the Experiment Station northeast of Garden City is Well 168 in Kansas Geological Survey Bulletin 55 and Finney County Well 26 in the annual series of the U. S. Geological Survey water-level reports. The well obtains its water from the Ogallala formation and Pleistocene deposits. It is 24 inches in diameter and 180 ft deep. When measured by Knapp in 1914, the depth to water was 71 ft. The measurement was made from a hole drilled at the base of the pump. At the end of 1954, the depth was 71.15 ft, and on January 17, 1955, it was 70.81 ft. The level on January 17, 1955, was slightly higher than in 1914. The highest water level recorded from 1914 to 1955 was 61.59 ft on October 21, 1949. The lowest level was 71.60 ft on April 24, 1941.

An observation-well program was started in Jewell County in 1934 [*Meinzer* and *Wenzel*, 1937, p. 62]. Measurements were started in 63 wells and have been continued in 16 of them. The fluctuations of Well 4-10-24ca [formerly Well 45] are typical of many of the Jewell County wells and are shown in the hydrograph in Figure 5. At the end of 1954 the water level was 20.6 ft below the land surface and was 9.4 ft higher than in 1934 when measurements were started. The highest water level during the period of record was 14.31 ft below the land surface on July 23, 1951; the lowest was 34.39 ft on December 21, 1940.

Oklahoma—An observation-well program was started in the Stillwater Creek area in Payne County, Okla., in 1934 [*Meinzer* and *Wenzel*, 1937, p. 231]. Periodic measurements of the water level were started in 17 wells and have been continued in seven wells. The average height of the water levels in feet above an arbitrary datum is shown in Figure 6. Also shown is the cumulative departure from average precipitation at Stillwater. As in most of the other areas, the water level rises when the precipitation is abundant and declines during drought periods. Because of the drought in

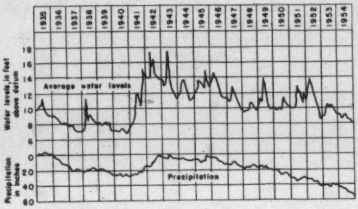

FIG. 6 – Average water level in feet above datum in wells in the Stillwater Creek area, Oklahoma, and the cumulative departure from average precipitation at Stillwater.

Oklahoma during the past three years, the water levels declined 6.4 ft from March 1952 to December 1954. The water levels are now 2.3 ft lower than in 1934.

Washington—An observation-well program was started in Kitsap County, Wash., in 1932 [*Paulsen, Sayre,* and others, 1955a, p. 134]. The hydrograph of Well 23-1-2C2 and the cumulative departure from precipitation at Bremerton are shown in Figure 4. Most of the annual precipitation occurs during the winter months. Accordingly, the water level rises during approximately the first half of each year and declines during the last half of the year. At the end of 1932 the water level was 52.0 ft below the land surface. At the end of 1954 the water level was 50.3 ft below the surface, or 1.7 ft above the level at the end of 1932. The highest water level during the period of record was 43.20 ft in June 1951; the lowest level was 60.32 ft in March 1945.

California—A well at Baldwin Park has been used as an observation well since 1903 [*Paulsen, Sayre,* and others, 1955b, pp. 49, 68]. This well is about 15 miles east of downtown Los Angeles and is in the San Gabriel River basin. The well is 200 ft deep and penetrates alluvial deposits of Recent and Pleistocene age. A hydrograph of this well is shown in Figure 7. The highest water level during the period of record was 331.1 ft above mean sea level in May 1916; the lowest level was 245.5 ft in November 1951. During the past few years the water level has been at a low stage comparable to the low stage reached in 1931.

Conclusions—Our ground-water supplies are derived from precipitation. Hence, the fluctuations of ground-water levels follow the precipitation trends. During periods of low precipitation the water levels decline, and during periods of abundant precipitation the water levels rise. In parts of the country that are in drought, the water table is now at a low stage; in other parts that have been receiving abundant precipitation, the water levels are at a high stage. No long-term trends of rise or decline of the water levels are discernible in areas not affected by pumping. As the weather cycle changes, many of the water levels that are now at a low stage will rise to a high stage and many water

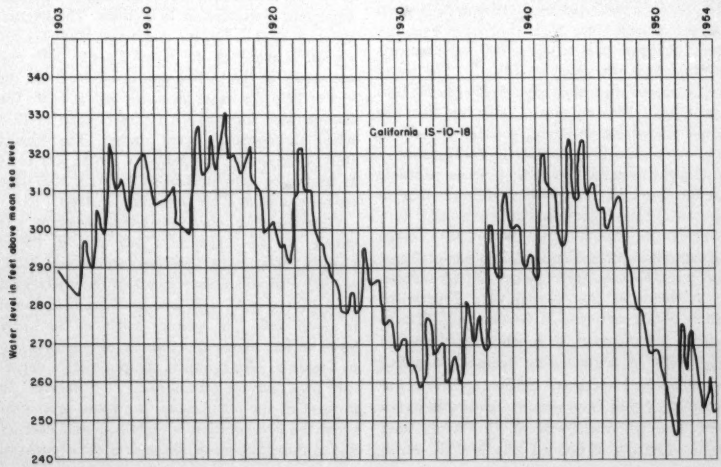

FIG. 7 – Hydrograph of Baldwin Park well (1S-10-18) in San Gabriel River basin in California

levels that are now at a high state will decline to a low stage. In some areas overdevelopment of the available water supply has been causing serious declines of the water level, and unfortunately, the overdevelopment has taken place in some of the best and most important aquifers.

In 1949, C. G. Paulsen, Chief of the Water Resources Division of the U. S. Geological Survey, made the following statement at the Third National Water Conservation Conference at Chicago, Ill.

"There is a widespread public impression that the overall ground-water supply of the United States is being depleted at an alarming rate, and that soon the supply may be exhausted. The truth is that there is no such thing as an overall nationwide depletion of ground water, although there are many local areas and a few larger regions where ground-water levels are declining so much as a result of heavy pumping that they might be regarded as overdeveloped. Nevertheless, large undeveloped supplies remain in many areas — indeed, the present total ground-water withdrawal in the United States represents only a fraction of the potential. Outside the relatively widely spaced areas of overdevelopment there is at present no progressive depletion of ground water."

This statement is just as applicable in 1955 as it was in 1949.

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Prediction of Ground-Water Levels on Basis of Rainfall and Temperature Correlations

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Abstract—A method for predicting ground-water levels in the glacial-outwash deposits in the Ohio River valley near Louisville involves development of curves by graphical correlation to define the effects of winter precipitation and winter temperature on recharge to the water table, and to determine the decline of the water table as water leaks into the Ohio River. Recharge occurs in the winter when evaporation and transpiration are at a minimum and when the soil is at or near field capacity. Several months is required for the water to percolate through about 60 feet of alluvium to reach the water table.

Introduction—During World War II, large withdrawals of ground water from the glacial-outwash deposits of the Ohio River valley at Louisville, Ky., resulted in a critical shortage of ground water. The U. S. Geological Survey, in cooperation with State and local agencies, made an investigation of the problem. An evaluation was made of natural recharge to the aquifer, of storage, and of pumpage. On the basis of information given in the cooperative report, the problem was solved by expensive conservation measures which included artificial recharge, installation of cooling towers, reuse of water, and redisign of equipment.

From the end of the War to 1950, pumpage and natural recharge were approximately in balance. At the start of the Korean conflict, industrial plants increased production schedules and water use increased. To avoid a recurrence of the 1943–44 shortage, studies were made of water-level records and related hydrologic factors in an effort to predict water levels far enough in advance to plan for and make necessary changes if it appeared that a second shortage might develop.

The problem was approached by graphical correlation. By this method separate effects were isolated as variables. Considered were change in water levels, change in storage, pumpage, rainfall, air temperature, ground-water recession curves, and induced infiltration from the Ohio River.

An area in which there was no pumpage and no river recharge was studied first. Relationships of precipitation and temperature to water-level changes under natural conditions were derived. These relationships were then transposed to pumped areas and additional correlations were made to find the relation among pumpage, storage changes, river infiltration, and water levels. From the curves thus derived, it was possible to predict water levels about nine months in advance for any proposed increase in pumping.

This paper will be limited to the prediction of water levels in an area under natural conditions.

Description of area—A section across the Ohio Valley in an area of no pumping about eight miles southwest of Louisville is shown on Figure 1. The valley, about four miles wide at this section, is partly filled with alluvial deposits of sand and gravel containing relatively little clay and silt. On top of the material is a cover of fine to very fine sand, silt, and clay, ranging in thickness from five to 40 ft. The total thickness of the valley fill ranges from about 80 to 130 ft. The valley floor is shale, which prevents upward flow into or downward flow from the sand and gravel. The valley fill is heterogeneous. Well logs show little correlation of individual beds from one place to another. During pumping tests, the aquifer temporarily behaves as though it were artesian, the overlying sand and clay, which have a lower permeability than the lower sand and gravel, acting as semiconfining beds. As pumping is continued, leakage occurs from the upper, tighter zones, and the valley fill behaves as a unit having water-table characteristics. The long-term storage coefficient for water-table conditions has been determined to average about 0.2 (0.2 cubic foot of water is yielded when the water level is lowered one foot in a column of aquifer having a cross section of one square foot). The permeability, as determined from pumping tests, is between 1000 and 1500 gallons per day per square foot.

Hydrology—The hydrology of the flood-plain area may be simplified for the purposes of this problem. Rainfall on the flood plain is disposed of by evapotranspiration, direct surface runoff, and infiltration into the soil. Part of the water entering the soil is retained temporarily as soil moisture, later to be removed by evaporation and transpiration, and part percolates downward to join the ground-water body. The ground water has a

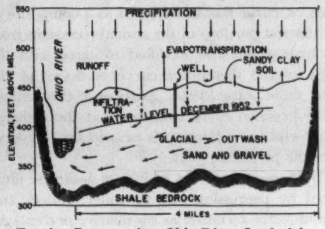

FIG. 1 – Cross section, Ohio River flood plain, southwest Louisville

gradient toward the river, indicating a lateral flow and a discharge to the river through its bed.

Figure 2 shows monthly means of precipitation, temperature, and month-end water levels at selected locations near Louisville. The average annual precipitation (80 years) of 42.86 inches is fairly well distributed throughout the year, being somewhat greater in winter and spring than in summer and fall. The mean temperature (80 years) is 57.0° F. The average period between killing frosts is October 23 to April 11.

Evapotranspiration is closely related to temperature. When considered in relation to the precipitation record, the period of greatest surplus water (precipitation less evapotranspiration) is the winter period.

The graph of average water levels indicates a low in January and a high in July. The decline during the period from September to February indicates that the loss of ground water to the river exceeds recharge from rainfall. The rise from February to July indicates that recharge exceeds discharge.

Recharge occurs seasonally, as indicated on the hydrograph (Fig. 3). This record is for a well eight miles southwest of Louisville and about two miles from the Ohio River. In wet years, such as 1950 and 1951, recharge exceeded discharge to the river by amounts sufficient to cause a rise in water levels of two or three feet. In drought years, 1953 and 1954, recharge was considerably less than discharge to the river and the combined effect resulted in annual declines of about three feet per year.

It is apparent that a correlation should exist between rainfall (supply) and the cyclic recharge. Recharge should enter the ground during periods of surplus water, or periods when precipitation exceeds evapotranspiration.

Index of recharge—Using the method described by *Thornthwaite* [1948], evapotranspiration was computed and subtracted from precipitation. The

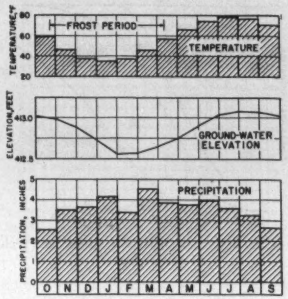

FIG. 2 – Monthly means at Louisville

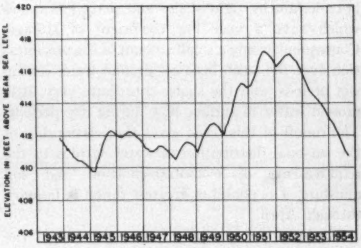

FIG. 3 – Graph of water levels in Well 51-8-1

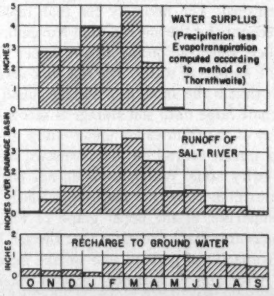
WATER SURPLUS
(Precipitation less Evapotranspiration computed according to method of Thornthwaite)
INCHES
RUNOFF OF SALT RIVER
INCHES OVER DRAINAGE BASIN
RECHARGE TO GROUND WATER
INCHES
O N D J F M A M J J A S

FIG. 4 – Monthly means of surplus water, runoff, and recharge to ground water

result, shown in the upper graph on Figure 4, indicates that the period of surplus water is November to April.

Another index of surplus water is surface-water runoff. The center graph on Figure 4 shows the monthly mean runoff of the Salt River at Shepardville. This station was selected because of the

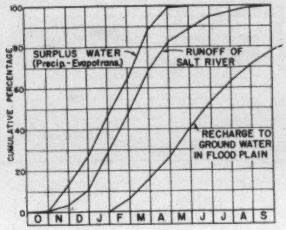

FIG. 5 – Cumulative surplus water, runoff, and recharge to ground water

geologic conditions. In contrast to the glacial-outwash area under study, the Salt River basin is underlain by tight shales and shaly limestones which have a very low coefficient of storage. Consequently only a small amount of the precipitation over the basin becomes ground water during wet periods, and the shales contribute very little ground water to surface flow during dry periods. The runoff of this basin gives the relationship of the seasonal distribution of water surplus to the requirements of evapotranspiration and soil moisture. The period of greatest runoff is January through April.

Soil moisture is depleted near the end of the growing season. After frost, when evapotranspiration requirements are greatly reduced, soil moisture is replenished. The necessity for that replenishment accounts for the low runoff in November and December, when, according to the upper graph, there is a surplus of water. The soil zone acts as a control; that is the amount of surface runoff does not become large until soil storage is satisfied. In that part of the Ohio valley under study, the soil exerts a similar control on the downward seepage to the water table. Water levels do not begin to rise until soil moisture has been replenished.

A comparison of the upper graph of Figure 4 with the center graph indicates that the soil has a storage capacity of perhaps four or five inches of water. After this is satisfied, ground-water recharge begins. The water table lies about 50 or 60 ft below the land surface. The material is fine grained, contains horizontal lenses of clay, and has a very low permeability in the vertical direction. A considerable time lag occurs during this phase.

The lower graph on Figure 4 shows the monthly accretion to the water table in the flood-plain area, computed from differences between observed monthly changes in water levels and monthly decline of the ground-water recession curve. The recession curve was constructed as a composite of the steepest portions of the annual recessions from the hydrograph and modified to agree with the shape of the theoretical curve of decay of the water table [*Jacob*, 1943]. Analysis of the ground-water recession curve indicates that the recharge from October to January is principally carryover from the preceding year.

The time lag evident in Figure 4 can be illustrated by expressing surplus water, runoff, and ground-water accretion as cumulative percentages of annual values as shown on Figure 5. Surplus water is available at a relatively uniform rate from November through March. The curve for runoff of the Salt River is parallel from December through March. The divergence in November and December depicts replenishment of soil moisture. The ground-water accretion curve for the flood plain reflects considerable time lag for vertical seepage. By the end of March, 88 pct of the annual surplus water has accumulated, whereas only 17 pct of the annual ground-water recharge has reached the water table.

The illustration shows that either surplus water or Salt River runoff could be used as an index of ground-water recharge in the flood plain; however, the prediction can be made earlier if the surplus-water index is used.

The best index period would be November through April. However, the period November through March produces satisfactory results and has the advantage of permitting the prediction to be made a month earlier. Much of the ground water is used in cooling processes where temperature is critical. An early prediction of a water shortage would indicate a need for use of city water (Ohio River source) for plant operation and if necessary for artificial recharge, before the temperature of the river water becomes too high for either purpose.

Correlations—The problem is to predict the low ground-water level, which usually occurs near the end of the calendar year. Several correlations can be made by graphical analysis of the variables.

A correlation using surplus water, determined as November-March precipitation adjusted for evapotranspiration computed by Thornthwaite's method and plotted against annual change in water levels, with an auxiliary curve for loss to the river, produced an unsatisfactory result. The residual errors when correlated with temperature demonstrated that either evapotranspiration differed from values computed by Thornthwaite's method, or else temperature entered the problem in

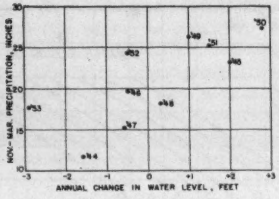

FIG. 6 – Plot of winter precipitation and annual change in water levels for years 1944–1953

some manner over and above its effect on evapotranspiration.

The method used here correlates winter precipitation with the annual change in water levels, with mdofications for winter temperature and loss of water to the river. Figure 6 shows the initial plot of November-March precipitation and annual change in water levels. A comparison of the plot with Figure 3 shows that data for years when water levels were high, such as 1952 and 1953, tend to fall to the left of an averaging curve, whereas those for years when water levels were low tend to fall to the right. It is apparent from this relationship that the scatter is related to the recession curve representing drainage to the river. An initial curve was drawn through the points on Figure 6 and the deviations of the points from this initial curve were plotted against ground-water elevation at the beginning of the year. A curve was fitted to this plot. Adjustments for elevation from this curve were applied to the base plot and a new curve was drawn. The process was repeated until no improvement could be obtained. The scatter on the adjusted plot of the base curve indicated that winter temperature was a significant factor. In a warm winter, evapotranspiration is greater than normal, so that winter precipitation alone is not a suitable index of the supply. The deviations of precipitation from the base curve were plotted against winter temperature (in degree-months of deviation from normal). A curve was drawn to this plot and the curve values were applied to the base plot. The three curves were adjusted to obtain the best fit.

The results are shown as Figure 7. The base curve is a plot of winter precipitation adjusted for winter temperature (index of available water), against annual change in water levels adjusted to normal elevation. The curve is for a condition of normal winter temperature and normal water-level elevation. The average slope of this curve indicates that ten inches of additional winter precipitation would cause a ground-water rise of about three feet.

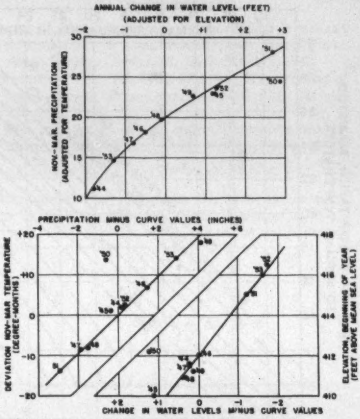

FIG. 7 – Correlation graphs for predicting water level in Well 51-8-1

Considering the storage coefficient of 0.2 (determined from pumping tests), ten inches of water should produce a total rise of 50 inches, or 4.2 feet; hence, it can be inferred that in the flood-plain area about 70 pct of the winter precipitation in excess of evapotranspiration and soil-moisture replenishment is recharged to ground water.

The year 1950 was the wettest in 80 years of record. Summer precipitation exceeded evapotranspiration in several months, and substantial recharge occurred after March 31. These factors account for failure of that year to plot on the curve.

The adjustment curve for temperature is of interest. Deviations of the winter precipitation from the base curve are plotted against winter temperature in degree-months, expressed as deviation from normal. The slope of the curve requires that an adjustment of one inch in the precipitation index is needed for each winter temperature increment of five degree-months. As a measure of evapotranspiration alone, the temperature factor curve produces winter losses more than double those computed by Thornthwaite's method. It appears, however, that temperature may enter the picture in ways other than its effect on evapotranspiration. It is possible that water viscosity plays a role. When there is surplus water, the runoff rate may be affected by viscosity. If so, in a warm period a more rapid runoff would reduce the time in which infiltration could take place.

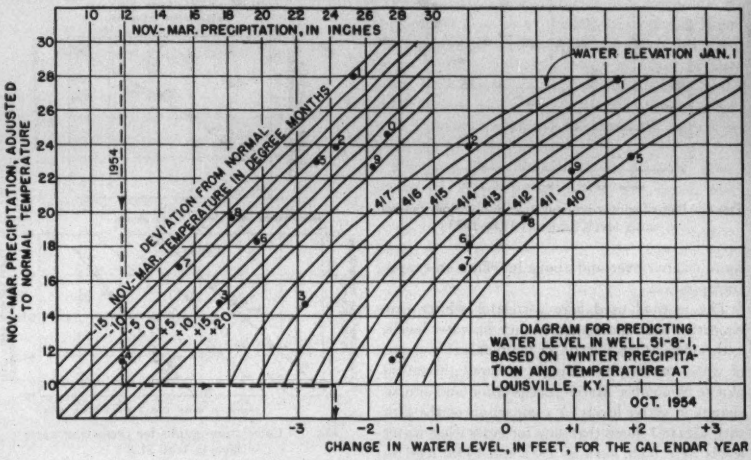
NOV.-MAR. PRECIPITATION, IN INCHES
NOV.-MAR. PRECIPITATION, ADJUSTED TO NORMAL TEMPERATURE
WATER ELEVATION JAN. 1
DEVIATION FROM NORMAL NOV.-MAR. TEMPERATURE, IN DEGREE MONTHS
1954
DIAGRAM FOR PREDICTING WATER LEVEL IN WELL 51-8-1, BASED ON WINTER PRECIPITATION AND TEMPERATURE AT LOUISVILLE, KY.
OCT. 1954
CHANGE IN WATER LEVEL, IN FEET, FOR THE CALENDAR YEAR

FIG. 8 – Diagram for predicting water levels in Well 51-8-1

Normally, ground-water flow rates increase with a rise in temperature. Recently, *Robinson* and *Rohwer* [1955] published experimental data in connection with canal-seepage studies. For the soils tested they found that seepage increased as temperature *decreased*. They concluded that changes in the volume of entrapped air in the soil might explain the phenomenon. Another factor is the effect of freezing and melting. The snowfall in the Louisville area averages 13.5 inches per year: snow remains on the ground for only a few days. However, the few days of slow melting, and possibly a slow rate of runoff at low temperature, provide an opportunity for greater recharge.

The straight-line elevation-adjustment curve is consistent with the theory for the recession curve of an artesian aquifer, that is, that the change in head per unit time is proportional to the head. The aquifer in the Louisville area is of the water-table type and ranges in thickness from 50 to 60 ft. The variation in transmissibility brought about by a change in saturated thickness would produce a curve rather than a straight line, although the amount of curvature would not be great. However, until more years of record are available additional refinement is not justified.

The correlation has been expanded into a diagram for easy use (Fig. 8). As an example, for the drought year 1954, enter the top scale with winter precipitation of 11.8 inches, drop vertically to the parameter for winter temperature deviation, +8.7°, move horizontally to the parameter of water elevation on January 1, 1954, 413.1 ft above mean sea level, and drop vertically to read the predicted water-level change for the year, about −2.5 ft.

Based on these correlations, a press release was issued in the spring of 1954 predicting a decline of about two to three feet in the water level in the unpumped area for the year 1954. In a 15-sq-mi area, the weighted average decline based on 14 observation wells was observed, in December 1954, to have been 2.8 ft.

For 1955, when the winter precipitation was 19.3 inches, winter temperature was 3.0 degree-months above normal, and water-level elevation at the beginning of the year was 410 ft, the outlook is for a water-level rise of nearly half a foot during the year.

Conclusions—(1) In the flood plain at Louisville most of the ground-water recharge occurs during the frost period, November–April, when evapotranspiration losses are small. During the growing season, soil-moisture requirements and potential evapotranspiration usually exceed rainfall so that water is not available for ground-water recharge. Droughts in the summer have very little effect on ground-water recharge.

(2) A time lag of several months is required for

recharge during the frost period to reach the water table. This time lag can be used effectively to predict water levels about nine months in advance.

(3) In a year having normal precipitation and temperature in the winter, about seven inches of water is recharged to the ground-water reservoir.

(4) Winter temperature plays a very important part in determining recharge. A deviation from normal November-March temperature of seven degree-months will alter the ground-water recharge by about one inch of water, or about 15 pct of the recharge for a normal year.

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Forecasting the Dry-Weather Flow of Pond Creek, Oklahoma; a Progress Report

William E. Clark

Abstract—Pond Creek in west-central Oklahoma drains an area of 319 sq mi above the gaging station near Fort Cobb, Caddo County. Ground water, contained in the Permian Rush Springs sandstone under water-table conditions, moves toward the creek at an almost unchanging rate. The discharge of ground water into the creek as dry-weather flow is modified by evapotranspiration and antecedent overland runoff. Multiple correlations have been computed relating the dry-weather flow to the water level in a well and to a factor indicative of the rate of evapotranspiration. A method for forecasting the factor indicative of evapotranspiration and one for forecasting the water level in the well during dry weather are given; the result is a method for forecasting the dry-weather flow of the Creek. Forecasts of dry-weather flow for seven and 21 days compare favorably with observed flows. The technique may be utilized to extend a forecast for several months.

Introduction—A method for forecasting the dry-weather flow of Pond Creek, in Caddo County, Okla., is outlined in this paper. The method is a product of hydrologic investigation in the Pond Creek basin by the U. S. Geological Survey.

Forecasts of dry-weather flow are becoming increasingly necessary for the efficient operation of modern integrated power systems and for the efficient operation of irrigation projects developed to full capacity. The need for streamflow forecasting is emphasized by the fact that the time of greatest need is often the time when streamflow is sustained only by contributions from surrounding groundwater bodies.

Merriam [1948] used an index based on water levels in wells to forecast the assured flow of the Susquehanna River for seven and 14 days. The method given in this paper depends on the correlation of dry-weather flow with the water level in a well and with a factor indicative of evapotranspiration. The method is rational; however, it is flexible enough so that forecasts can be made for any period of time.

This paper gives, first, a description of the basin; next, a general concept of ground-water flow to the Creek; then, correlations relating the dry-weather flow to the water level in a well and to a factor indicative of evapotranspiration; and, finally, techniques for forecasting the factors that have been related to the dry-weather flow together with examples of dry-weather forecasting.

Geology and general features of the basin—Pond Creek, known locally as Cobb Creek, drains an area of 319 sq mi above the U. S. Geological Survey gaging station in west-central Oklahoma. The basin is in Caddo County except for short extensions northwestward into Washita and Custer Counties (Fig. 1). At Weatherford, near the northern boundary of the basin, the mean annual precipitation is 28.77 inches, and the mean annual temperature is 60.3°F. The normal monthly precipitation ranges from 0.84 inch in January to 4.47 inches in May, and the average monthly temperature ranges from 37.4° in January to 82.3°F. in July.

The Rush Springs sandstone is at the surface throughout most of the basin. It is a friable reddish-brown crossbedded to regular-bedded sandstone, which, as shown by well logs, is as much as 334 ft thick where the section is complete. The outcrop area has been eroded so extensively that the thickness of the sandstone varies greatly. In the western part of the basin, the relatively impermeable Cloud Chief formation overlies the Rush Springs sandstone. The Cloud Chief formation consists of impure dolomite, gypsum, gypsiferous sandstone, and shale. Another relatively impermeable formation, the Marlow formation, underlies the Rush Springs sandstone. It consists of 120 ft of red even-bedded sandstone and red shale, regular beds of fine white sand, and much disseminated gypsum. These formations dip southwestward at the rate of 20 to 40 ft/mi [*Davis*, 1950].

A narrow band of alluvium composed of fine-grained sand and clay overlies the Rush Springs sandstone along Pond Creek and its tributaries. At some places the alluvium is more than 90 ft thick, but at most places it is much thinner.

The surface of the drainage basin is a moderately rolling plain except along the streams, where the local relief commonly reaches 100 ft or more. Most of the uplands is in cultivation; a part is used for pasture, but in a few places only scrub oaks grow. On the bottom lands near the streams, where the water table is near the surface, a fringe of phreato-

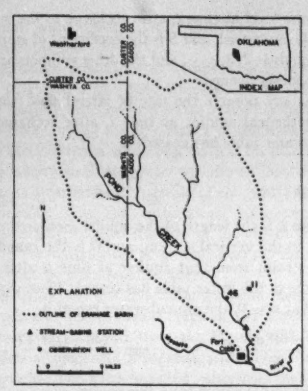

FIG. 1 – Map of the Pond Creek drainage basin, showing the locations of Wells 11 and 46 and stream-gaging station

phytes grow – underbrush, elm, cottonwood, and oak trees.

The Rush Springs sandstone, which contains large quantities of water under water-table conditions, is the source of ground-water runoff to Pond Creek. Wells drilled into the Rush Springs sandstone supply water for domestic, stock, and irrigation purposes. The first irrigation well in the basin was completed in 1948; at the end of 1949 there were eight irrigation wells, and since then the number has increased rapidly.

HYDROLOGY

Circulation—Precipitation is the source of the ground water in the Rush Springs sandstone. The ground water moves toward places of discharge, such as pumped wells, vegetation that is transpiring ground water, areas where the water table is so near the land surface that ground water is discharged as ground-water runoff. Except for the wells, these places of discharge are generally along

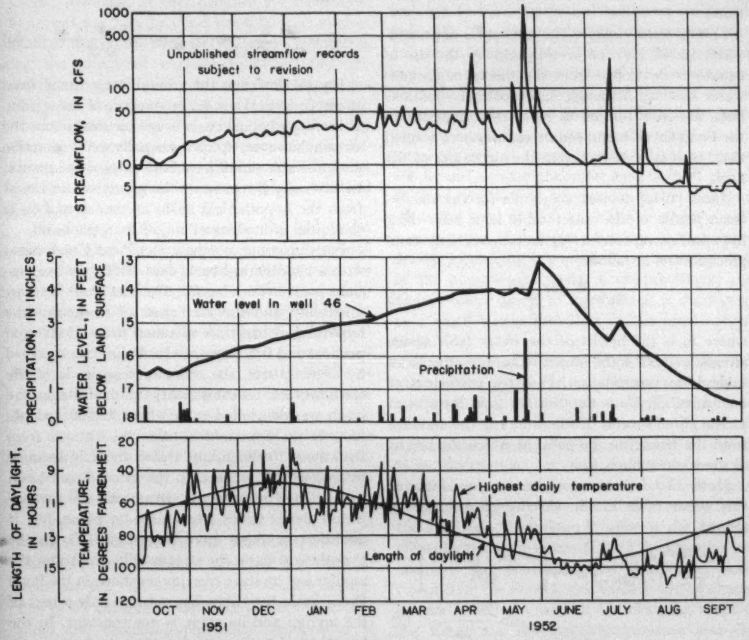

FIG. 2 – Typical variation of the streamflow of Pond Creek, water level in Well 46, precipitation at Weatherford, length of daylight in basin, and highest daily temperature at Weatherford

Pond Creek and its tributaries, and therefore nearly all ground water in the basin is either discharged into Pond Creek and its tributaries as ground-water runoff or is evaporated or transpired near these streams.

Surface water—The U. S. Geological Survey operates a gaging station on Pond Creek, 2.7 mi north of Fort Cobb (Fig. 1). Figure 2 shows a typical hydrograph of the flow of Pond Creek as measured at the gaging station. The records from the gaging station are rated as good except those for periods of ice effects and no-gage-height record, which are rated as poor. A good rating indicates that, in general, the error in the daily records is believed to be less than ten per cent. A poor rating indicates that the error is probably more than 15 pct. Before 1952 there were no known diversions from Pond Creek. Since 1952, however, small quantities of water have been pumped from the Creek for irrigation during the growing season. The diversions from the Creek are estimated to be as much as three cubic feet per second (cfs) at times.

Ground-water runoff—The mechanics of ground-water runoff may be investigated by the use of equations developed from the theory of ground-water motion. Although mathematical equations have not been formed to represent conditions in the Pond Creek basin, equations have been formed that, to some extent, depict the mechanics of the flow.

Jacob [1943] devised a formula for the steady-state profile of the water table in a very thick hypothetical aquifer having uniform recharge from precipitation as follows

$$h_0 = \frac{W}{T}\,\frac{(ax-x^2)}{2} \qquad (1)$$

where h_0 is the height of the water table above stream level, W is the rate of recharge to the water table from precipitation, T is the coefficient of transmissibility, a is the distance from the stream to the ground-water divide, and x is the distance from the stream to the point at which the height of the water table is h_0.

Jacob also devised a formula for the decline of this water table in the absence of recharge as follows

$$h = \frac{16a^2W}{\pi^3T}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^3}\exp\left[\frac{-(2n-1)^2\pi^2Tt}{4a^2S}\right]\cdot\sin\frac{(2n-1)\pi x}{2a} \qquad (2)$$

where h is the height of the water table above stream level at time t, after recharge to the water table has ceased, and S is the coefficient of storage, n equals 1, 2, 3, $\cdots$, and the other symbols are as previously defined.

At any point x the rate of lateral flow from a hypothetical aquifer at time t, after recharge to the water table has ceased, is

$$Q = -TL\frac{\partial h}{\partial x} \qquad (3)$$

where L is the length of the aquifer measured normal to the vertical section, and Q is the runoff to the stream from that aquifer at time t, after recharge to the water table has ceased. Thus, evaluated at $x = 0$, the ground-water runoff is

$$Q = \frac{-8WaL}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\frac{-(2n-1)^2\pi^2Tt}{4a^2S} \qquad (4)$$

The initial runoff from this aquifer is

$$Q_0 = -WaL \qquad (5)$$

so that

$$Q = \frac{8Q_0}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\frac{-(2n-1)^2\pi^2Tt}{4a^2S} \qquad (6)$$

Eq. (6) describes the ground-water runoff from the hypothetical aquifer on one side of the stream. If the hypothetical basin is symmetrical about the stream, however, (6) serves equally well to describe ground-water runoff from both sides of the stream. In this case, Q represents the ground-water runoff from the hypothetical basin at time t, and Q_0 is the initial ground-water runoff from the basin.

For discussion, compare the Pond Creek basin with a hypothetical basin that fulfills the assumptions made in deriving (6). The coefficient of transmissibility and the coefficient of storage of the hypothetical basin are assumed to be 15,000 gpd per foot and 0.1, respectively. From data reported by *Davis* [1950], the order of magnitude of the coefficient of transmissibility at one site in the basin was concluded to be about 13,000 gpd per foot. In the hypothetical basin the distance from the stream to the ground-water divide is assumed to be 20,000 ft, whereas in the Pond Creek basin the distance between the stream and the ground-water divide varies from place to place, but it doubtless averages more than 20,000 ft. In the hypothetical basin the stream fully penetrates the aquifer and its stage remains constant; in the Pond Creek basin the Creek has cut into only a part of the aquifer and its stage is not constant. In the hypothetical basin ground water is discharged only into the stream, whereas in the Pond Creek basin

ground water is discharged also from wells and phreatophytes.

Although ground-water withdrawals from wells for irrigation in the Pond Creek basin are increasing rapidly, the ground-water runoff is reduced gradually, owing to the distance of the wells from the creek. From a study of a method for determining the proportion of water withdrawn from a well that is diverted from a stream [*Theis*, 1941], it was concluded that the withdrawals have not yet appreciably affected the flow of the creek. Therefore, the withdrawal of ground water from wells will not be considered further.

Because of the evapotranspiration near the Creek and the changing stage of the Creek, the ground-water runoff from the Pond Creek basin differs significantly from that of the hypothetical basin. Beyond a few hundred yards from the Creek and the bordering phreatophytes, however, the water table is not appreciably affected by evapotranspiration or by changes in the stage of the Creek; therefore, at that distance the movement of ground water in the Pond Creek basin is comparable to that in the hypothetical basin. Disregarding the effects of evapotranspiration and the changing stage of the Creek, the ground-water runoffs from the hypothetical basin and from the Pond Creek basin may be compared by comparing their aquifer constants and by comparing the decline of the water table in the hypothetical basin with the fluctuation of the water table in the Pond Creek basin.

The derivative of Q with respect to time in (6) will show that the ground-water runoff decreases at a slower rate with a longer distance to the ground-water divide, a smaller coefficient of transmissibility, and a larger coefficient of storage. In the Pond Creek basin the distance to the ground-water divide is longer, the coefficient of transmissibility is probably smaller, and the coefficient of storage is doubtless larger than in the hypothetical basin. Therefore, on the basis of aquifer constants, it is concluded that in the absence of recharge the ground-water runoff from the Pond Creek basin decreases at a slower rate than does the ground-water runoff from the hypothetical basin.

Figure 3 is a hydrograph of Well 11 (see Fig. 1), which is in the Rush Springs sandstone. The fluctuations of its water level are typical of those in wells not affected measurably by evapotranspiration or by changes in the stage of the Creek. The small and comparatively rapid fluctuations of water level shown in Figure 3 are caused by changes in atmospheric pressure rather than by variations

FIG. 3 – Hydrograph of Well 11

in recharge or discharge. The slow decline of the water level, about 3½ ft in more than six years of record, is the result of a decrease in recharge to the aquifer. Except for 1949, the annual precipitation in the basin has been below normal since 1947. Because water must percolate downward through more than 30 ft of fine-grained rock, a large quantity of water is in transit to the water table; and, accordingly, the rate of recharge to the water table changes only slowly. Thus, recharge continues into periods of drought.

The decline of the water table in the absence of recharge in the hypothetical basin was computed from (2). The water table midway between the stream and the ground-water divide was computed to decline nine per cent of its height above stream level in the first two years after recharge to the water table ceases, and 25 pct in the first six years after recharge ceases. Because the height of the water table above stream level at Well 11 is nearly 100 ft, and because the water level in Well 11 has declined only 3½ ft in six years, it can be seen that the water level in Well 11, which is roughly midway between the stream and the ground-water divide, is declining at a much slower rate than that in the hypothetical basin. Correspondingly, the ground-water runoff to Pond Creek is decreasing at a much slower rate than in the hypothetical basin.

The ground-water runoff from the hypothetical basin in the absence of ground-water recharge is computed from (6) to decrease 15 pct in the first year and 27 pct in the first 3 years. On the basis of a comparison of aquifer constants and of water-table fluctuations, it was concluded that the ground-water runoff from the Pond Creek basin declines at a slower rate than that from the hypothetical basin. Therefore, in view of the slow decline of ground-water runoff from the hypothetical basin, it was concluded that the ground-water runoff from the Pond Creek basin would be almost constant if it were not for the changing stage of the Creek and the evapotranspiration near the Creek.

On the whole, therefore, ground water moves

toward the Creek at an almost unchanging rate. The discharge into the Creek as ground-water runoff, however, is varied by the changing stage of the Creek and is reduced by evapotranspiration near the Creek.

Relation of the dry-weather flow to water levels and to the index of streamflow loss

The dry-weather flow of Pond Creek varies with the rate at which ground water moves toward the Creek and with the rate of evapotranspiration. Other factors being equal, the rate at which ground water moves toward the Creek varies with the gradient of the water table. The water-table gradient does not change significantly except near the Creek, where the water table fluctuates in response to evapotranspiration and changes in the stage of the Creek. During dry weather, the stage of the Creek changes slowly so that the gradient near the Creek changes chiefly with the fluctuations of the water table. Therefore, the dry-weather flow of the Creek changes with the fluctuations of the water table near the Creek and with variations in the rate of evapotranspiration.

Well 46—Evapotranspiration and changes in the stage of the Creek cause most of the changes in the water level in Well 46. Figure 1 shows the location of Well 46 (about 500 ft from the Creek) and Figure 2 shows a typical hydrograph of its water level. The well is in the Rush Springs sandstone. Its water level is drawn down by the transpiration of ground water from nearby phreatophytes and by the evaporation of ground water from the soil where the water table is near the land surface. The well is near enough to the Creek that its water level responds to changes in the stage of the Creek, but it is not so close that its water level reflects only the stage of the Creek. Because its water level fluctuates with the stage of the Creek and with evapotranspiration, the fluctuation is typical of the fluctuation of the water table near the Creek.

Index of streamflow loss—The rate of evapotranspiration is influenced by many factors such as solar radiation, air temperature, humidity, air movement, depth to water, type of vegetation, and density of vegetation. *Blaney* [1952] correlated evapotranspirational data with monthly temperatures, monthly percentage of yearly daylight hours, and growing period. In a similar manner a factor indicative of the rate of evapotranspiration in the Pond Creek basin was developed from climatological data. This factor, called the index of streamflow loss is the product of the ten-day highest temperature above freezing at Weatherford and the length of daylight in hours in the basin. The ten-day highest temperature above freezing is the average of the highest air temperature above freezing on the day for which the index is desired and the nine preceding days. Typical variations of the highest daily air temperature at Weatherford and the length of daylight in the basin are shown in Figure 2.

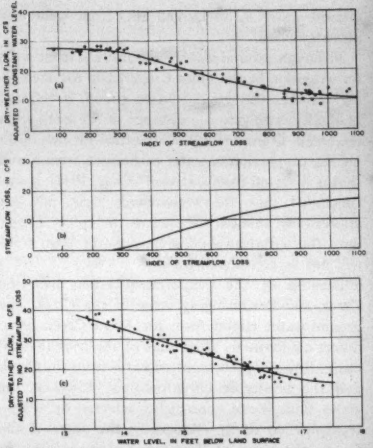
DRY-WEATHER FLOW, IN CFS ADJUSTED TO A CONSTANT WATER LEVEL
(a)
INDEX OF STREAMFLOW LOSS
STREAMFLOW LOSS, IN CFS
(b)
INDEX OF STREAMFLOW LOSS
DRY-WEATHER FLOW, IN CFS ADJUSTED TO NO STREAMFLOW LOSS
(c)
WATER LEVEL, IN FEET BELOW LAND SURFACE

FIG. 4 – Results of correlations relating water levels and index of streamflow loss to dry-weather flow; (a) relation of the index of streamflow loss to dry-weather flow that has been adjusted to a constant water level in Well 46; (b) relation of the index of streamflow loss to streamflow loss; (c) relation of water level in Well 46 to dry-weather streamflow that has been adjusted to no streamflow loss.

Correlation of the water level in Well 46, the index of streamflow loss, and the dry-weather flow—The fluctuations of the water table in Well 46 are typical of the fluctuations of the water table near the Creek, and the index of streamflow loss is indicative of the rate of evapotranspiration. Therefore, the dry-weather flow of Pond Creek may be related to the water level in Well 46 and to the index of streamflow loss. Accordingly, the dry-weather flow of Pond Creek, as measured at the gaging station, was correlated with the water level in Well 46 and with the index of streamflow loss. The correlations were based on data collected from January 1951 through August 1954.

The results of the correlations are shown in Figure 4. The standard error of estimate for the

correlations is 2.2 cfs and the index of multiple correlation is 0.96.

Figure 4a shows the relation between the index of streamflow loss and the dry-weather flow that has been adjusted to a constant water level in Well 46. This relation does not change when the index of streamflow loss is less than 280. The index of streamflow loss is less than 280 only during the winter when the phreatophytes are dormant and when there is little or no evapotranspiration. The difference between the flow at the flat portion of the curve, where the index of streamflow loss is less than 280, and the flow at any other point on the curve is referred to in this report as streamflow loss. The relation between streamflow loss and the index of streamflow loss, as shown in Figure 4b, was constructed from Figure 4a. Figure 4c shows the relation between the water level in Well 46 and the dry-weather flow that has been adjusted to no streamflow loss.

Forecasting the dry-weather flow of Pond Creek

The dry-weather flow of Pond Creek may be estimated from the relationships shown in Figure 4 if the water level in Well 46 and the index of streamflow loss are known. For example, if the water level in Well 46 were 16 ft below land surface and if the index of streamflow loss were 625, then the dry-weather flow of Pond Creek adjusted to no streamflow loss would be 21 cfs, as shown on Figure 4c, and the streamflow loss would be 10 cfs, as shown on Figure 4b. Hence, the dry-weather flow of the Creek would be 11 cfs. A forecast of the dry-weather flow of Pond Creek, therefore, can be made from forecasts of the index of streamflow loss and the water level in Well 46.

Forecasting the index of streamflow loss—The index of streamflow loss is based on the length of daylight hours in the basin and on the ten-day highest temperature at Weatherford. Times of sunrise and sunset are published for a few years in the future by the U. S. Naval Observatory in the *American Ephemeris and Nautical Almanac*. As the length of daylight hours can be computed from the times of sunrise and sunset, only the ten-day highest temperature at Weatherford need be forecast.

In order to determine the range of air temperatures at Weatherford, the ten-day highest temperature at Weatherford was computed at weekly intervals from 1944 through 1953. Figure 5 shows the highest and the average of the ten-day highest temperatures above freezing for the period 1944–53. Inasmuch as the range between the highest and the average, in most instances, is less than ten degrees, satisfactory forecasts of the index of streamflow loss can be made on the basis of the temperature record shown in Figure 5.

Forecasting the water level in Well 46—The water level in Well 46 fluctuates with the amount of ground water stored in the aquifer near the well and with the changes of atmospheric pressure. Evapotranspiration near the well affects the water level in much the same way as pumping from a nearby well. Generally, when the rate of evapotranspiration is greatest, the rate at which the water level is drawn down is greatest; and when the total drawdown is great, the rate of recovery is great. Accordingly, multiple correlations were computed, relating the change of the water level in Well 46 to the stage of the water level in Well 46 and to the factor indicative of evapotranspiration, the index of streamflow loss. The change of the water level in seven days was related to the water level at the beginning of the seven days and to the index of streamflow loss at the end of the seven days.

The resulting relations are shown in Figure 6. Figure 6a shows the relation between the changes of the water level in Well 46 in seven days and the water level in Well 46. Figure 6b shows the relation between the change of the water level in seven days and the index of streamflow loss. The standard error of estimate for the correlation is 0.06 ft and the index of multiple correlation is 0.97.

The relationships shown in Figure 6 are not well defined throughout the entire range of the variables. Part of the lack of definition in the relationships is due to the fact that, in determining the change of the water level in Well 46 in seven days, measurements affected by overland runoff at either

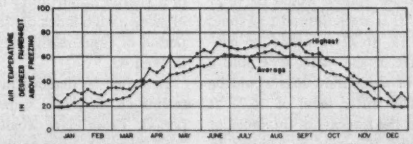

FIG. 5 – Highest and average of the ten-day highest temperatures above freezing at Weatherford, 1944–53

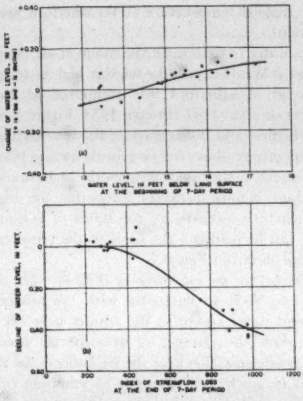

FIG. 6 – Change of the water level in seven days in Well 46 during dry weather; (a) as related to the water level in Well 46; (b) as related to the index of streamflow loss.

the beginning or the end of the period could not be used. Furthermore, the correlations did not take into account the fluctuations of the water level in Well 46 caused by changes in the atmospheric pressure or by the slow change in the stage of the Creek during dry weather. As indicated by an index of multiple correlation of 0.97, however, most of the changes in the water level in Well 46 during dry weather were related to the water level in Well 46 or to the index of streamflow loss.

The relationships shown in Figure 6 provide a means for forecasting the water level in Well 46 in dry weather. For example, assume that the water level is 16 ft below land surface on June 1 and that a forecast of the index of streamflow loss for June 8, is 900. From Figure 6a, the change of the water level as related to the stage of the water level is a rise of 0.09 ft, and from Figure 6b the change of the water level as related to the index of streamflow loss is a decline of 0.36 ft. Hence, during the week the net change of the water level is a decline of 0.27 ft. A forecast, therefore, of the water level in Well 46 for June 8 would be 16.27 ft below land surface. If it were desired to extend the forecast to June 15, 16.27 ft would be considered the initial stage of the water level and a forecast of the index of streamflow loss would be made for June 15. The water level of 16.27 ft below land surface and the forecast of the index of streamflow loss for June 15 would be applied to Figure 6ab to obtain the change of the water level between June 8 and June 15. Thus, assuming dry weather, forecasts can be made of the water level in Well 46 for any desired period.

Examples of dry-weather forecasting—Forecasts of dry-weather flow may use forecasts of the index of streamflow loss based on either the highest or the average of the ten-day highest temperature records shown in Figure 5. If based on the highest, the forecasts are more conservative than if based on the average, because the forecast of streamflow loss and the decline of the water level in Well 46 are greater than if based on the average. When computing for only a few days, the forecast of the change in water level in Well 46 is small, and, correspondingly, its effect on the forecast of the dry-weather flow is small. For extended periods, however, the forecast of the change of the water level may be large and its effect on the forecast considerable.

The method of forecasting has been applied to the records of Pond Creek for the period January 1951 through August 1954. Forecasts for seven-day and 21-day periods were based on indexes of streamflow loss computed from the highest of the ten-day highest temperatures, as shown in Figure 5. The observed streamflow is compared to the forecast of the dry-weather flow for seven-day and 21-day periods in Figure 7. Points plotted below the line of equality represent forecasts of dry-weather flow that were more than the observed flow. Points plotted above the line of equality represent forecasts that were less than the observed flow. Several points were below the line of equality in both the seven-day and the 21-day forecasts. However, only three points in the plot of the seven-day forecasts and two points in the 21-day forecasts were below the line of equality by more than two cubic feet per second.

The plotted points, in general, are scattered above the line of equality but they tend to cluster near the line. Part of the scatter above the line is the result of overland runoff, and part is the result of using an index of streamflow loss that is high at times. The scatter is greater for the 21-day forecasts than for the seven-day forecasts. The greater scatter of the 21-day forecasts is the result of a greater opportunity for rainfall and the result of using a high index of streamflow loss for a longer period of time on the forecasts of the water level in Well 46.

In order to demonstrate the flexibility of the technique, forecasts were made for an extended period. From data available on September 27, 1952, forecasts were made of the dry-weather flow at weekly intervals through June 1953. Forecasts

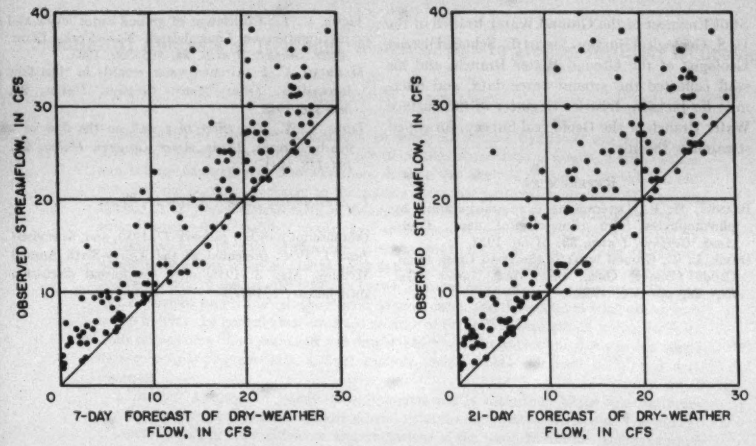

FIG. 7 – Comparison of seven-day and 21-day forecasts of dry-weather flow with observed streamflow

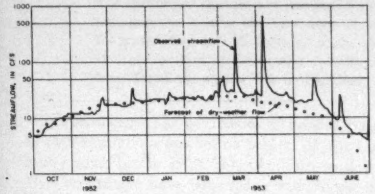

FIG. 8 – Comparison of forecasts from September 27, 1952, of dry-weather flow with observed streamflow

of dry-weather flow are compared to the observed streamflow in Figure 8. Thus the forecast shown on October 4 is for one week, the one on October 11 is for two weeks, and so on. The period for which the forecasts were made is not only one of little overland runoff but also one suited to extended forecasts because of the rapidly declining rate of streamflow loss in the autumn and the negligible amount of streamflow loss in the winter.

The extended forecasts were based on the indexes of streamflow loss computed from the average of the ten-day highest temperature, as shown in Figure 5. The average of the ten-day highest temperature was occasionally lower than the actual ten-day highest temperature, thus making the forecast of the index of streamflow loss less than the actual index of streamflow loss. For this reason, the forecast of streamflow loss is small sometimes, and the forecast of the dry-weather flow is greater than the observed flow.

The forecasts were based on the assumption that there would be no overland runoff. There was little overland runoff during the period of the forecast until March (Fig. 8); afterward, however, there was considerable overland runoff. Therefore, the observed flow exceeds the forecast of dry-weather flow appreciably after February.

The correlations upon which the forecasts were based were developed from data collected during the period from January 1951 through August 1954. Data from this same period also were used to test the forecasting procedure. Admittedly, it is not strictly correct to use that period to test the forecasting procedure. Nevertheless, if the correlations were revised periodically, forecasts of the dry-weather flow of Pond Creek could be made with only a small decrease in accuracy.

CONCLUSIONS

Though based on scant data, the method of forecasting the dry-weather flow of Pond Creek gives satisfactory results. In fact, for forecasts over an extended period, the results are excellent. It appears that the techniques involved in the method may be applied to other basins if modified to take into account individual basin characteristics.

Acknowledgments—The hydrologic investigations in the Pond Creek basin were under the general direction of Penn P. Livingston, formerly

Staff Engineer of the Ground Water Branch of the U. S. Geological Survey. Stuart L. Schoff, District Geologist of the Ground Water Branch, and his staff collected the ground-water data, and Sherman K. Jackson, District Engineer of the Surface Water Branch of the Geological Survey, furnished streamflow records.

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Numerical Analysis of Regional Water Levels to Define Aquifer Hydrology

ROBERT W. STALLMAN

Abstract—Two fundamental methods for studying aquifer hydrology are now in use. The first, applied many years ago, consists of detailed observation of aquifer inflow, outflow, and storage changes, and their variations in time. By analysis of these observations, estimates of the perennial recharge to the aquifer and other pertinent hydrologic data are obtained, all as gross characteristics of the aquifer. The need for greater detail gave rise to a second fundamental method: special field tests, such as pumping tests, by which the hydrologic coefficients could be measured in a comparatively short time. In order to evaluate properly the ability of an aquifer to serve as a source of perennial water supply, the geology and hydrology of the aquifer must be known in some detail over its entire area. The first method cannot supply the necessary detail in most cases, and the second method cannot ordinarily provide the needed areal coverage because of the lack of appropriate testing facilities. Thus an auxiliary third approach was sought which would combine the features of a simple data-collection program with a final analysis yielding both adequate detail and areal coverage.

A method designed to satisfy these requirements is described. Water-level altitudes, usually observed in the course of more general ground-water studies, are analyzed by numerical methods, using finite-difference approximations of the basic differential equations which describe ground-water flow. Analytical methods are given for nonsteady flow through homogeneous and nonhomogeneous aquifers. Both direct and statistical solutions are shown. The hydrologic factors are computed as functions of transmissibility, and for the nonhomogeneous aquifer the variations of transmissibility in space are computed also from the water-level data. Knowledge of the absolute value of any one of the hydrologic factors at some location in the aquifer permits conversion of the computed functions to absolute terms for all the aquifer flow field studied.

Introduction.—The occurrence of ground water in rock formations has been a subject of intensive study since before 1900. Investigations to define that occurrence have been made with increasing emphasis on the collection of quantitative data necessary to determine the ability of aquifers to serve as a source of water supply. The development of these investigations has taken place in what might be categorized as three overlapping phases, corresponding, for the most part, to the types of basic data currently required for engineering application. From 1900 to about 1935, academic field studies were undertaken in selected areas for tracing ground-water movement through specific aquifers and analyzing that movement in relation to the hydrologic cycle. The later studies of this period were made on the premises that the recharge to or the discharge from the aquifer could be measured by collecting and analyzing appropriate field data, and that this information could be used for estimating the amount of ground water available for perennial withdrawal from the aquifer.

As the use of ground water assumed greater economic significance, during the period 1935–40, still more emphasis was placed on the production aspects. Questions concerning potential well yield, the effects of ground-water withdrawal on pumping lift, and the potentialities for induced recharge began to be included in the evaluation of proposed water-supply facilities. The process of answering the foregoing questions required analyzing the ability of the aquifer to store and transmit water and determining the availability of surface-water sources that might be used in artificially recharging the aquifer. These activities prompted the rapid development of field techniques that would assure collection of the desired quantitative information. Of course, the well-known work of Thiem, Slichter, and King, dating back to the turn of the century, had already produced a number of important quantitative techniques. However, these techniques in general required rather lengthy field tests, because data analysis had been developed only for steady flow. In 1935, Theis constructed a new springboard for quantitative studies: the equation of nonequilibrium flow to a well. Use of equations describing the nonequilibrium state generally requires a shorter field test and permits a more comprehensive analysis, compared to use of the corresponding equations of steady flow. Furthermore, analysis of nonsteady

ground-water flow permits direct evaluation of the storage capacity of the aquifer, whereas such evaluations ordinarily cannot be made by analysis of steady flow. Nonequilibrium equations, such as the Theis equations, also provide a means for predicting the rates of drawdown in both time and space in the vicinity of a pumped well, once the aquifer constants are known, thereby encouraging well-field design through the use of engineering techniques rather than empirics.

The nonequilibrium-flow techniques have been extended by many students of ground water, notably *Ferris* [1949] and *Jacob* [1950]. Most of this work has been devoted to the development of analytical equations that can be used for computing the coefficients of transmissibility and storage from data collected in special field tests. These coefficients are the quantitative measures of the ability of the aquifer to transmit water and to take water into or release it from storage, respectively. Some attention has been given also to computing the rate of accretion, which is the rate at which water is added to the aquifer by virtue of downward percolation after precipitation [*Jacob*, 1944], and to evaluating streams as sources of induced infiltration [*Rorabaugh*, 1948]. Current research continues to supply additional analytical equations for the various combinations of hydrologic activity, aquifer geometry, and testing facilities, which might be available for observation.

The increasing demand for ground water [*Guyton*, 1949; *MacKichan*, 1951] has given rise to a need for rapid expansion of production facilities. There is in evidence a growing concern regarding the effects of expanding ground-water production within comparatively small regions of an aquifer. Interference between individual wells or well fields, or general water-level declines in some places, or both may reduce the efficiency of the whole production system to such an extent that further local development may not be economically feasible. To assess the magnitude of expected water-level changes in a given region, the aquifer geology and hydrology must be known in quantitative detail over most of the area. The current need for this type of information on a regional basis marks the need for the entry of ground-water hydrology into a third phase. Hitherto nearly all the analytical equations available for resolving test data have been founded on the assumption that the aquifer can be idealized as a homogeneous system of infinite or semi-infinite extent, and that flow is in either one or two dimensions. These equations are particularly useful for computing

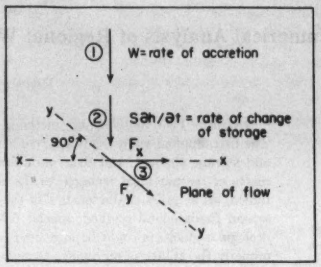


FIG. 1 – Flow components at a point in the flow field

the hydraulic constants from the observed configuration of small portions of the flow field near hydraulic controls such as streams or wells, but they are much less effective for calculating the coefficients on a regional basis, because the tested area is usually a very small, and perhaps not an average, segment of the aquifer under study. Thus where it is required to define thoroughly the hydraulic characteristics of the nonhomogeneous aquifer, conventional tests would have to be made at a great number of locations within the aquifer. The limited availability of conventional testing facilities precludes such a detailed study over the entire aquifer.

The flow field—Although for some field situations the analysis of ground-water flow can be quite complex, the flow will be considered here for convenience as two-dimensional, nonsteady, and occurring in horizontal aquifers. Examination of three basic flow components, shown schematically in Figure 1, will aid materially in understanding the fluid dynamics at each point in the flow field. These components may be described briefly as follows: (1) Accretion to the water table W in the general case, is the net rate at which water is gained or lost through the aquifer surface in response to external forces. The gain or loss, as an example, may result from leakage through semipermeable confining beds of an artesian aquifer. (2) Changes in the volume of water stored in the aquifer augment or diminish the rate of flow at each point by an amount equal to $S(\partial h/\partial t)$, where S is the coefficient of storage of the aquifer. The direction of this flow component is parallel to the direction of accretion, and the sum of the two components equals the net rate at which water is added to or lost from the zone of saturation. (3) The net amount of water movement, $F_x + F_y$, through the zone of saturation is related to the

coefficient of transmissibility T and its variation from place to place in the aquifer, and to the configuration of the piezometric surface. The relation between variations in head in the aquifer and transmissibility is given by application of Darcy's law.

For a homogeneous aquifer, it can be shown that the relationship among the three flow components described above, for any point in the flow field, is

$$T(\partial^2 h/\partial x^2 + \partial^2 h/\partial y^2) = S\partial h/\partial t - W \quad (1)$$

Eq. (1) may be rewritten for convenient grouping of the hydrologic factors, as

$$\partial^2 h/\partial x^2 + \partial^2 h/\partial y^2 = (S\partial h/\partial t - W)/T \quad (2)$$

From (2) it is apparent that the hydrologic properties of the aquifer can be evaluated at any point in space and time simply by measuring the second differentials of head at that point. However, practical measurement of these differentials at a point is not possible.

The transition from point to regional analysis may be made by using approximations of the head differentials in space as shown by *Southwell* [1946]. By this technique, head differentials that apply to finite areas can be estimated from water-level altitudes known at widely spaced points. Then, (2) can be applied to contiguous finite areas over the entire aquifer surface for quantitative regional evaluation of the hydrology.

Bennett [1952] has demonstrated an important application of the regional approach to water-level analysis, using flow-net studies. A flow net was constructed by graphical procedures to duplicate the observed configuration of the piezometric surface in the Baltimore area of Maryland. After the observed piezometric surface was reproduced as a flow net, the aquifer properties were computed from a comparison of the flow net with pumpage. The numerical methods proposed herein are, in effect, similar to the solution by Bennett, except that a numerical model is substituted for the flow net.

Analysis of water-level data from homogeneous aquifers—The relationship among the variables of flow through a homogeneous aquifer is given by (2). Estimates of head differentials can be obtained by applying the methods of *Southwell* [1946]. Assume, as shown in Figure 2, that the aquifer is subdivided into squares of equal area a^2 by a system of lines equally spaced a finite distance apart. This subdivision may be viewed as an approximation of the area $dxdy$ of a corresponding grid used in orthodox mathematics. Applying calculus to obtain a solution, in effect, is a process for conveniently adding together the effects of variables over an infinite set of the areas $dxdy$. For problems that involve complex boundary conditions, solutions by calculus are correspondingly difficult. In order to simplify the process of obtaining a solution, simple algebraic addition may be substituted for calculus in the more difficult integration problems. However, algebraic addition cannot be applied to an infinite set of areas like $dxdy$. Hence, in order to reduce the infinite set of areas to some finite number, which can be processed conveniently by algebraic methods, the infinitesimal $dxdy$ is 'expanded' to an approximation a^2 where a is small compared with the distance across the flow field.

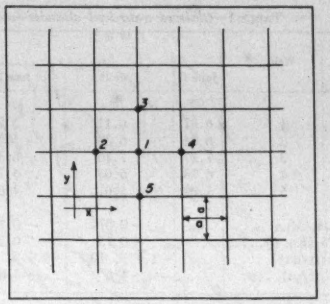


FIG. 2 – Finite-difference grid on flow field

The nodes formed by intersection of the grid lines in Figure 2 are presumably points at which head is known. At node 1, according to *Southwell* [1946, p. 19], the second derivatives of h can be approximated by the relation

$$\partial^2 h/\partial x^2 = (h_2 + h_4 - 2h_1)/a^2 \quad (3)$$

and

$$\partial^2 h/\partial y^2 = (h_3 + h_5 - 2h_1)/a^2 \quad (3a)$$

also, it can be said that

$$\partial h/\partial t = (h_{1,t} - h_{1,t+\Delta t})/\Delta t \quad \text{or,}$$

$$\Delta h/\Delta t = \Delta_t h_1/\Delta t \quad (4)$$

Substituting these approximations in (2), there follows the finite-difference form of (2) which can be used for numerical analysis of water-level data

$$h_2 + h_3 + h_4 + h_5 - 4h_1 = (S\Delta_t h_1/\Delta t - W)a^2/T \quad (5)$$

In the above derivation it has been assumed that S and W are uniform over the area represented by

TABLE 1 – *Observed water-level altitudes for a homogeneous aquifer and computed accretion rates*

Well	1947							
	June 11	June 19	June 25	July 3	July 19	Oct. 23	Oct. 30	Nov. 7
	ft[a]	ft	ft	ft	ft	ft	ft	ft
1	6.87	6.11	5.71	4.70	3.81	3.19	3.29	3.15
2	6.24	6.39	5.74	5.14	4.40	3.16	3.30	3.16
3	7.27	7.16	6.37	5.45	4.62	3.88	3.82	3.49
4	6.78	6.03	5.78	4.57	3.87	3.12	3.10	2.50
5	5.89	5.61	4.69	3.76	2.88	2.86	2.28	2.33
$(\Delta_t h_1/\Delta t)_{wt\ av}$	...	−0.074	−0.106	−0.075	...	...	−0.014	...
$\sum_1^5 h$ (Eq. 6)	...	+0.75	−0.26	+0.12	...	...	−0.66	...
W (ft/day)	...	-1.1×10^{-3}	-9.9×10^{-3}	-8.1×10^{-3}	...	...	$+1.9 \times 10^{-3}$	...
W (ft/yr)	...	−4.0	−3.6	−3.0	...	...	+0.7	...

[a] Arbitrary datum.

nodes 1 through 5 (Fig. 2), and that the equation defining the manner in which h varies over that area can be expressed with sufficient accuracy as a polynomial in x and y.

If the values of T and S are known, (5) affords a means of computing the rate of accretion W using water-level observations at five wells, located according to the array shown in Figure 2. As an example, consider the water-level data (Table 1) selected from a five-well array where a is 400 ft. These data were collected from a shallow unconfined aquifer in Indiana, consisting of medium sand extending from the land surface downward about 30 ft to a dense, impermeable clay. A thin very sandy soil caps the aquifer materials and supports a predominantly grassy cover. Other field data indicate that the transmissibility is about 6000 gpd/ft or 800 ft²/day. The storage coefficient is estimated to be 0.1. At this site the accretion rate changed in immediate response to slight precipitation. Inasmuch as water levels were measured only once each week, fluctuations in the rate of accretion could not be observed in detail. Obviously, rates of accretion computed from the available data would not be representative values if significant changes in those rates occurred between water-level measurements. Accordingly, the data shown in Table 1 were selected as representing periods during which precipitation was constant and zero. Therefore the accretion rates computed for the intervals shown should be representative and a comparatively smooth function of time.

Substitution of the hydraulic constants, and the well spacing in (5) yields

$$W = 0.1\Delta_t h_1/\Delta t - 5 \times 10^{-3} \sum_1^5 h + E \quad (6)$$

where W is in feet per day, $\sum_1^5 h$ is the sum of all head terms on the left-hand side of (5), and E is the error, which is herein assumed negligible, introduced by the approximations inherent in (3) and (4). From the periodic water-level measurements given in Table 1, estimates of $\Delta_t h_1/\Delta t$ can be made. Consider, for example, the data shown for June 19. The hydrograph slope for Well 1 on that date would be approximately the difference in water-level altitudes observed on June 11 and June 25, divided by the number of days between these dates: (5.71 − 6.87)/14. It is to be observed that the rate of change of water levels in the individual wells in the array area was not uniform in space. Therefore the hydrograph slope at Well 1 might not be as representative as desirable. An arbitrarily weighted value can be used as follows

$$\left(\frac{\Delta_t h_1}{\Delta t}\right)_{wt\ av} = \frac{\Delta_t h_2 + \Delta_t h_3 + \Delta_t h_4 + \Delta_t h_5 + 4\Delta_t h_1}{8\Delta t} \quad (7)$$

The computed values of $(\Delta_t h_1/\Delta t)$ shown in Table 1 were computed by (7). Values of W are shown in Table 1, as computed by means of equation 6 in which $(\Delta_t h_1/\Delta t)_{wt\ av}$ has been substituted for $\Delta_t h_1/\Delta t$. These are effective average values which apply to the time intervals used for calculating the $(\Delta_t h_1/\Delta t)_{wt\ av}$ values.

The change in W with time reflects in part an increasing depth to water below the land surface, which was 0.7, 1.4, and 2.3 ft, for the dates June 19, 25, and July 3, respectively. More detailed records, and more careful evaluation of the hydraulic constants at this site, would permit more exact measurement of the accretion rate and its variations with time and weather. In turn, these data could be used for a continuous and direct evaluation of evapotranspiration losses, if used in

conjunction with measurements of soil-moisture content.

In the example given, the coefficients of both transmissibility and storage were known. If only the transmissibility is known and if S and the accretion rate are uniform over the aquifer area considered, the latter two unknowns can be computed if water-level data are available (taken simultaneously) from two or more separate arrays. Data from each array, used in (5), permit solving for S and W. If S and W vary in space, their variations and absolute values also can be computed if more data are available. In general, as the complexity of these variations in space increases, the quantity of data required for solution also increases.

Analysis of water-level data from nonhomogeneous aquifers—The general differential equation describing the relationship among h, T, S, and W in space and time for two-dimensional nonsteady flow at a point in a nonhomogeneous aquifer is written as

$$T(\partial^2 h/\partial x^2 + \partial^2 h/\partial y^2) + (\partial T/\partial x)(\partial h/\partial x) + (\partial T/\partial y)(\partial h/\partial y) = S\partial h/\partial t - W \quad (8)$$

In this case, it is assumed that all parameters vary in space, and that W varies in both space and time. The manner of variation of T in space is of particular interest. Although they cannot be measured directly, regional trends of these variations can be estimated by assuming that T varies as some arbitrary function of x and y, that may be expressed in the form

$$T_{(x,y)}/T_{(0,0)} = 1 + f(x, y) \quad (9)$$

It is then possible to solve for specified unknowns in (9) using a group of finite-difference equations constructed from water-level data and (8). Another substitution must be made in constructing the finite-difference equations in order to account for the storage and accretion factors. If these factors cannot be evaluated except by the configuration of the piezometric surface, two methods are available for eliminating them from the computation of transmissibility variations. Under certain conditions (as will be seen), it can be assumed that

$$S\frac{\partial h}{\partial t} - W = 0 \quad (10)$$

Also, it will be shown that, for any case, storage and accretion may be written as

$$S\frac{\partial h}{\partial t} - W = f(h, T, x, y) \quad (11)$$

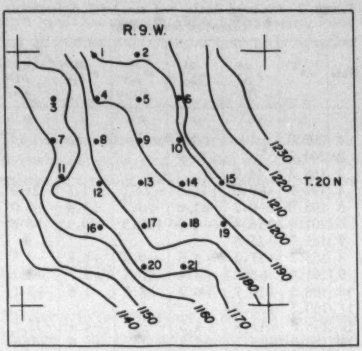


FIG. 3 – Water-table contour map of selected part of Cimarron terrace, Oklahoma (after [*Reed*, 1952]), showing well locations used for numerical analysis

Use of (8), (9), and (10) for analyzing the water-level data permits the evaluation of the manner of variation of T in space. Use of (8), (9), and (11) permits individual evaluation of all hydrologic parameters as a function of space, if the values of $(\partial h/\partial t)_{x,y}$ are known.

Part of a water-table contour map [*Reed* and others, 1952] is shown as Figure 3. Numbers are arbitrarily assigned to well locations 1 through 21. The area represented by these wells was chosen for study only as a convenient means for presenting the numerical methods that follow. Water-level altitudes are known to the nearest 0.5 foot at each of the numbered locations. The distinct advantage of these data over others that might be selected from the literature is that the well locations are evenly spaced, thereby simplifying the computations.

The general characteristics of the aquifer can be evaluated qualitatively by means of the most elementary principle of ground-water flow. At positions distant from the ground-water divide, the volume rate of flow is approximately constant along comparatively short segments of any flow line. Therefore, by Darcy's law, it can be seen that the hydraulic gradient along the flow line is approximately inversely proportional to the transmissibility. Note the low gradient in the general area of nodes 2, 5, 9, 13, 17, and 18, and compare with the hydraulic gradient on either side, on the perimeter of the area being considered. Qualitatively, it can be presupposed that transmissibilities are comparatively high near the wells shown in the center of Range 9 West, and that lower values may

TABLE 2 – *Observed heads and computed differentials, Cimarron terrace data*

Node	h	$a\frac{\partial h}{\partial x}$	$a\frac{\partial h}{\partial y}$	$a^2\frac{\partial^2 h}{\partial x^2}$	$a^2\frac{\partial^2 h}{\partial y^2}$	$a^2\left(\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}\right)$
	ft	*ft*	*ft*	*ft*	*ft*	*ft*
1	202.0	...	+3.7	...	...	...
2	204.7	...	+16.9	...	...	...
3	168.3	44.0	...	...	...	...
4	192.7	+9.0	+11.5	−22.1	+1.1	−21.0
5	195.0	−0.2	+4.6	+3.7	+4.3	+8.0
6	201.0	+16.4	−4.0	+29.5	−20.9	+8.6
7	165.5	+25.8	...	...	...	...
8	183.2	+11.2	+6.6	−9.9	+6.1	−3.8
9	191.0	+6.0	+4.4	−0.5	−1.7	−2.2
10	198.3	+10.2	+6.2	+8.9	−1.8	+7.1
11	160.5	+25.9	...	...	...	...
12	178.5	+11.4	+4.5	−10.7	−4.4	−15.1
13	186.0	+5.2	+5.2	−1.2	+0.6	−0.6
14	192.5	+9.7	+4.8	+10.5	+2.2	+12.7
15	209.7	+27.0	...	...	...	...
16	168.1	...	+20.6	...	...	...
17	181.6	+9.0	+3.3	−7.5	+2.5	−5.0
18	187.6	+3.8	+6.9	−2.7	−8.9	−11.6
19	190.9	...	...	...	...	...
20	178.9	...	...	...	...	...
21	172.5	...	...	...	...	...

be expected on either side where the hydraulic gradient is larger. A significant change in accretion rate over the flow field also might produce this water-table configuration. For example, if the water table were near the land surface, permitting a high evapotranspiration loss, or even discharge through the surface to form swamplands, a similar configuration might be produced. However, there is no evidence to support the assumption of significant influence from spatial variations in accretion rates.

The numerical approximation of the head differential expressed by (3) and (3a) is founded on the premise that only three wells are available for computing the differential terms. Better estimates can usually be obtained if more than three wells are used. Observe, in Figure 3, that there are six wells on the line joining Wells 2 and 20, which can be used to compute values of $\partial h/\partial y$ and $\partial^2 h/\partial y^2$ using Bickley's tables for differentiation [*Southwell*, 1946, pp. 229–237]. Thus from the tables cited the following sample equations may be written for node 13 in terms of the other nodes or well numbers on the 6-well line indicated:

$$a(\partial h/\partial y)_{13} = (6h_{20} - 60h_{17} - 40h_{13} + 120\,h_9 - 30h_5 + 4h_2)/120 \quad (12)$$

$$a^2(\partial^2 h/\partial y^2)_{13} = (-5h_{20} + 80h_{17} - 150h_{13} + 80h_9 - 5h_5)/60 \quad (13)$$

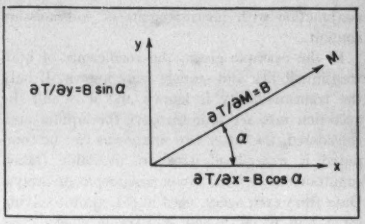


FIG. 4 – The nonhomogeneous aquifer with linearly changing transmissibility

where a is the grid or well spacing. Observed head values, and head differentials computed by means of Bickley's tables, are shown in Table 2 for the 21 selected well locations. Only those differentials are given that are used in subsequent computations. Several combinations of assumed hydrologic conditions will be introduced in the following discussion, simply for the purpose of demonstrating procedure. None of the assumed conditions are presumed to be completely applicable to the hydrology of the area selected for analysis.

The velocity of flow through the aquifer at any position on a flow line equals the sum of the values of $S(\partial h/\partial t) - W$ existing along the flow line from its origin to the position being considered. If the values of $S(\partial h/\partial t) - W$ are reasonably uniform in space, the velocity of flow past any position far distant from a ground-water divide is usually large compared with the value of $S(\partial h/\partial t) - W$ at that position. This conclusion is equally applicable to small finite areas in the flow field. The configuration of the water table is dependent on both the rate at which water flows through the aquifer and the rate of addition to that flow. If the velocity of flow in the zone of saturation is very large compared with $S(\partial h/\partial t) - W$, it is apparent, then, that (10) can be used as an approximation.

As an example of a direct solution, utilizing a minimum amount of water-level data, assume the condition expressed by (10). Also assume, as shown on Figure 4, that T increases at a maximum rate B in direction M, α degrees from x. Then $\partial T/\partial x$ and $\partial T/\partial y$ of (8) can be expressed in terms of B and α. Employing the stated conditions at Well 13, (see Fig. 3), substituting in (8) the appropriate head differentials given in Table 2, and dividing through by T_{13}, there follows

$$-0.6 + 5.2aB(\sin\alpha + \cos\alpha)\frac{1}{T_{13}} = 0 \quad (14)$$

Also, from the conditional assumptions shown in Figure 4 it is evident that

TABLE 3 – *Eq. (8) applied to nodes for interpretation of data*

Node	Finite-difference form of (8)
5	$-8.0 = (-0.2\cos\alpha + 12.6\sin\alpha)aB/T_9$
6	$-8.6 = (25.0\cos\alpha + 4.6\sin\alpha)aB/T_9$
9	$+2.2 = (6.0\cos\alpha + 4.4\sin\alpha)aB/T_9$
10	$-7.1 = (17.3\cos\alpha + 6.2\sin\alpha)aB/T_9$
13	$+0.6 = (5.2\cos\alpha + 5.8\sin\alpha)aB/T_9$
14	$-12.7 = (22.4\cos\alpha - 7.9\sin\alpha)aB/T_9$
17	$+5.0 = (9.0\cos\alpha + 13.3\sin\alpha)aB/T_9$
18	$+11.6 = (-7.8\cos\alpha + 30.1\sin\alpha)aB/T_9$

$$T_{14} = T_{13} + aB\cos\alpha \qquad (15)$$

or

$$T_{14}/T_{13} = 1 + aB(\cos\alpha)/T_{13}$$

Writing (8) for Well 14, dividing by T_{13}, and substituting in (15), there follows

$$12.7 + aB(4.8\sin\alpha + 22.4\cos\alpha)/T_{13} = 0 \qquad (16)$$

Simultaneous solution of (14) and (16) yields $\alpha = 131°$ and $aB/T_{13} = 1.1$. Usually such a high value of aB/T will indicate faulty assumptions or erroneous data. Extropolating this result in the direction $-M$ for a distance a would indicate the existence of the physically nonsensical negative transmissibility.

Experience with the data given in Table 2 has shown that direct solutions for computing the hydraulic characteristics lead to results which cannot be reconciled with the facts apparent from qualitative considerations. Also, the values of aB/T computed around the loop of one grid square should close on themselves if the solutions are satisfactory. Reasonable closure is not obtained with the data used here. Part of the difficulty may be due to inaccuracy of data, however, it is highly probable that the simple variations stated by the conditional equations cannot be applied to data at a small number of points in order to define regional characteristics. The influence of local defects in data accuracy and nonconformance with the conditional assumptions can be minimized, however, by applying the same assumptions to a greater number of nodes, and using a least-squares solution to obtain the regional characteristics.

As an example, the conditional assumptions just employed will be used for the area represented by the two lines of wells, 2–20 and 6–21 inclusive (see Fig. 3), using T_9 as the reference transmissibility and taking x as positive toward the east. The equations derived by substituting the conditional assumptions and data from Table 2 in (8) are given in Table 3. In the least-squares solution of the eight equations given in Table 3, the system must first be normalized. Observe that each equation has the form

$$D(\cos\alpha)\frac{aB}{T_9} + E(\sin\alpha)\frac{aB}{T_9} = G$$

The two normalized equations needed to solve for the two unknowns, that is, α and aB/T_9, are then written in terms of the above constants as follows

$$(\cos\alpha)\frac{aB}{T_9}\Sigma D^2 + (\sin\alpha)\frac{aB}{T_9}\Sigma DE = \Sigma DG \qquad (17)$$

$$(\cos\alpha)\frac{aB}{T_9}\Sigma DE + (\sin\alpha)\frac{aB}{T_9}\Sigma E^2 = \Sigma EG \qquad (18)$$

Referring to the constants in the eight equations in Table 3, and summing them in the manner indicated above, it will be found that (17) and (18) can now be rewritten as

$$(1631.0\cos\alpha - 15.7\sin\alpha)\frac{aB}{T_9} = -649.9 \qquad (17a)$$

$$(-15.7\cos\alpha + 1416.7\sin\alpha)\frac{aB}{T_9} = 344.8 \qquad (18a)$$

Simultaneous solution of (17a) and (18a) yields $\alpha = 149°$ and $B = 0.46\ T_9/a$. The value of α is in general agreement with the obvious features displayed by the water-level contours and the numerical order of aB/T (0.46) is reasonable. Similar application of the statistical solution to the lines of wells 1–16 and 2–20 produces values of $\alpha = 20°$, and $B = 0.66\ T_9/a$, where T_9 is used as the reference transmissibility.

The conditional assumptions employed need not be restricted to linear variation, as was used in the analysis just described. The term $f(x, y)$ of (9) can be assigned arbitrarily in the statistical solution. As an example of the use of more complex functions, the solution shown on Figure 5 was obtained, assuming that the situation described by (10) prevails and using the following conditional equation, letting $x = y = 0$ at node 12

$$T_{(x,y)}/T_{12} = 1 + bx + cy + dx^2 + exy + fy^2 \qquad (19)$$

In (19) the letters b, c, d, e, and f represent constants, to be found from analysis of the water-level data. Differentiation of (19) yields

$$\frac{1}{T_{12}}\left(\frac{\partial T_{(x,y)}}{\partial x}\right) = b + 2dx + ey \qquad (20)$$

$$\frac{1}{T_{12}}\left(\frac{\partial T_{(x,y)}}{\partial y}\right) = c + ex + 2fy \qquad (21)$$

Eq. 8 was divided by T_{12} and then equations 19, 20, and 21 were substituted for the transmissibility

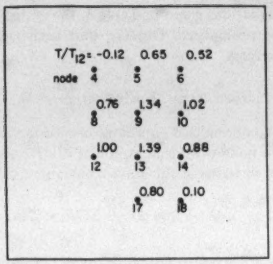


FIG. 5 – Relative transmissibility values in the non-homogeneous aquifer, assuming $S(\partial h/\partial t) - W = 0$

ratio and its differentials. Appropriate values of head differentials were taken from Table 2. The finite-difference equation for node 12 where $x = y = 0$, for example, is found to be

$$-\frac{15.1}{a} + 11.4b + 4.5c = 0$$

or, letting the distance a be unity

$$-15.1 + 11.4b + 4.5c = 0 \qquad (22)$$

Similarly for node 9, where $x = y = 1$ (if a is considered as unity) the finite-difference equations proves to be

$$-2.2 + 3.8b + 2.2c + 9.8d + 8.2e + 6.6f = 0 \quad (22a)$$

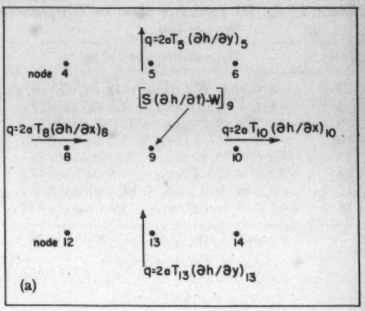
An equation like (22) or (22a) was constructed for each of the eleven nodes shown in Figure 5. The resulting set of eleven equations was normalized and solved for a least-squares fit to the conditional assumptions, letting the distance a be unity. The solution, shown on Figure 5 was found to be

$$T_{(x,y)}/T_{12} = 1 + 0.84x + 0.08y - 0.45x^2 + 0.19xy - 0.32y^2 \quad (19a)$$

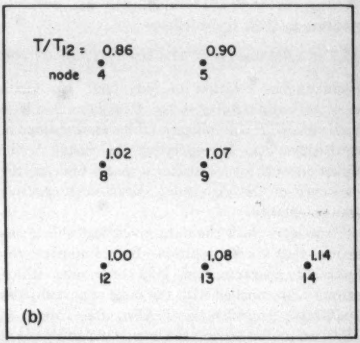
Note the negative T indicated by the solution for node 4.

If sufficient water-level data are available, the storage and accretion term can be set equal to a function of T and head differentials, as shown by (11), thereby including their effect in computing the variations of T in space. As an example of this approach, note Figure 6a. The algebraic sum of the rate of change in storage and the rate of accretion in the area 4-6-14-12-4 equals the net flow through the sides of the area. As an approximation of the discharge through the side 4-6, let

$$q_{4\text{-}6} = 2aT_5(\partial h/\partial y)_5 .$$



(a)



(b)

FIG. 6 – Relative transmissibility values taking into account changes in storage and the accretion rate; (a) components of flow; (b) relative transmissibility values using the approximations shown in (a)

Similar approximations can be made for flow through each of the other three sides. Letting $[S(\partial h/\partial t) - W]_9$ be the mean value for the area 4-6-14-12-4, it can be seen that

$$\frac{4a^2\left[S\left(\frac{\partial h}{\partial t}\right) - W\right]_9}{T_{12}} = 2a\left[T_5\left(\frac{\partial h}{\partial y}\right)_5 - T_{13}\left(\frac{\partial h}{\partial y}\right)_{13} + T_{10}\left(\frac{\partial h}{\partial x}\right)_{10} - T_8\left(\frac{\partial h}{\partial x}\right)_8\right] \Big/ T_{12} \quad (23)$$

The (S, W) terms were defined as functions of transmissibility and head by equations like (23)

for nodes 4, 5, 8, 9, 12, 13, and 14 of Figure 3. By substituting equations like (19) and (23), and the appropriate values of head differentials in (8) for each of these nodes, a set of 7 finite-difference equations for estimating variations of T in space is obtained. The solution is shown in Figure 6b. Of the 7 equations used in the process only three, those written for nodes 4, 5, and 12, were satisfied to a sensible degree by the statistical solution. In part, the poor statistical relationship probably arises from the inaccuracy of the head-differential estimates for external nodes like 2 and 7 (see Fig. 3). For example, in using node 7 to estimate $(\partial h/\partial x)_7$, an extrapolation of the piezometric surface through the known points is used. The irregularity of the surface makes it highly probably that extrapolation of the known surface to the left of node 7 will not be in good agreement with its actual position. Therefore the estimate of $(\partial h/\partial x)_7$, based on such an extrapolation, will not be accurate. Use of a large number of equations (compared with the number of unknowns) or the exclusive use of internal nodes for computing head differentials in a statistical solution may reduce the effects of these errors on the final result.

Solely for the purpose of illustration, using the results shown in Figure 6b, values of

$$a^2[S(\partial h/\partial t) - W]/T_{12}$$

for nodes 4, 5, and 12 were computed, and found to be +20.3, −6.3, and +14.0 respectively. The average value is +9.4. The value of T may be assumed as approximately 1×10^4 ft²/day. In the solution, a was set equal to unity, whereas in reality it is one mile. Accordingly T must be put in the same units:

$$1 \times 10^4/(5.28)^2 10^6 = 3.6 \times 10^{-4} \text{ mi}^2/\text{day}.$$

Then

$$\left[S\left(\frac{\partial h}{\partial t}\right) - W\right]_{\text{mean}} = 3.6 \times 10^{-4} \times 9.4 = 3.4 \times 10^{-3} \text{ ft/day} \tag{24}$$

Letting S = 0.1 [*Reed* and others, 1952, p. 28] and $\partial h/\partial t = -0.02$ ft/day (Reed, personal communication, 1954), $W = 3.4 \times 10^{-3} - 2.0 \times 10^{-3} = -5.4 \times 10^{-3}$ ft/day, or about −2 ft/yr.

A number of equations like

$$\frac{\partial h}{\partial t} - \frac{W}{S} = \frac{CT_{(0,0)}}{S} \tag{25}$$

where C is a constant, are obtainable for a given area by the technique just described. Where $\partial h/\partial t$ can be observed, a set of equations similar to (25) can be solved for mean-square values of W/S and $T_{(0,0)}/S$. Then, if the absolute values of T are known, both S and W can be evaluated. The term $\partial h/\partial t$ is very largely dependent on the values of W and S in regions far distant from boundary influences, and in those regions the numerical evaluation of W and S from water-level data will be difficult. But in the regions near strong boundary influences, high accuracy could be obtained if C and T are correct.

In the discussion of computing techniques the number of nodes was limited to 21. The use of additional water-level data in the same area could have increased the amount of detail per unit area in the computed result. Mathematical reproduction of such complex detail for an entire aquifer would be very difficult. On the other hand, statistical analysis of the entire aquifer may smooth the results to such an extent that important local hydrologic features do not appear in the final analysis. The need for both the gross and the detailed studies can be met by separate analysis of the one set of data for the aquifer. First, the gross characteristics of the transmissibility variations can be obtained by utilizing all data available in a statistical solution. From this solution, mean values of transmissibility could be obtained which would apply to comparatively large segments of the aquifer area. Second, the variations of the hydrologic parameters within each segment could be obtained by analysis of the data available in the individual segments. The hydrologic properties computed in the second phase of analysis can then be written in terms of the gross values computed in the first step, thereby relating all hydrologic parameters to a common standard of reference.

Analysis of water-level data alone is not sufficient to obtain absolute values of the hydrologic parameters, but such analysis can be used to compute relative values. Once the relative values are known, only one absolute value must be known anywhere in the system in order to describe the hydrology in absolute terms.

In the data used here, water-level altitudes were observed on a regularly spaced grid which greatly simplified computation of the head differentials. Ordinarily water-level data are not available in such a regular pattern. If the head values are known along lines of a rectangular grid, and the wells are not equally spaced, numerical approximations of the head differentials can be computed by using La Grange's interpolation formula, as indicated by H. E. Skibitzke of the Geological Survey (personal communication, 1955). For those cases in

which water-level data are not on a rectangular grid, numerical values of the head differentials can also be obtained, but with less ease. First head is set not equal to an arbitrary function of (x, y) as follows

$$h_{(x,y)} = h_{(0,0)} + f(x, y) \qquad (26)$$

say, for example,

$$h_{(x,y)} = h_{(0,0)} + bx + cy + dx^2 + exy + fy^2 \quad (27)$$

Then the observed data $h_{(x,y)}$, $h_{(0,0)}$, x, and y are inserted in (27) for each of a cluster of wells, and the resulting set of simultaneous equations is solved for the coefficients a, b, c, etc. Differentiation of (27) then yields the estimates needed for substituion in (8).

Application of (8) to areas of finite size restricts its use to areas in which the removal or addition of water to the aquifer is spread over the aquifer surface. Therefore, well arrays cannot be used if they span such hydraulic controls as recharging or discharging wells, or surface-water bodies hydraulically connected with the ground-water flow system. The comparatively small withdrawals made for domestic use ordinarily will not affect the regional flow characteristics. A high density of domestic wells, such as found in some suburban developments, may not fit the conditions tacitly assumed in applying (8) to regional analysis. Water-level observations near active domestic systems may not reflect the regional flow system accurately. However, it is believed that if the water-level data observed reflect the regional flow in the aquifer, the hydrology of the aquifer can be defined by numerical analysis of the piezometric surface.

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Tidal Fluctuations of Water Level Observed in Wells in East Tennessee

R. M. RICHARDSON

Abstract—Semidiurnal water-level fluctuations of tidal period have been observed in wells completed in the Chickamauga limestone of Middle and Late Ordovician age in east Tennessee. The periodic oscillations of the water level are similar to fluctuations in artesian pressure that in other localities have been recognized and correlated with earth tides.

Tidal fluctuations of ground-water levels in an inland locality were apparently first observed in a flooded coal mine at Dux, Bohemia [*Klonne*, 1879]. Observations of such fluctuations in a well at Maghull, England, were reported by *Roberts* [1881], who ascribed those fluctuations to both solar and lunar tidal disturbances. Observations of variations of tidal period in the yield of flowing wells were made by *Young* [1913], near Cradock, South Africa. *Robinson* [1939] presented a paper in which he gave data regarding tidal fluctuations in water level in a well at Carlsbad, N. Mex., and a well at Iowa City, Iowa. In this paper Robinson demonstrated that the fluctuations of water levels in these wells are coincident with the earth tides caused by the Moon and Sun. In the same year *Theis* [1939] reported on fluctuations in water level in artesian wells near Carlsbad and Conchas Dam, N. Mex., in phase with the Moon's rotation. He ascribed the fluctuations to elastic dilation and compression of water contained in the aquifer due to bulging and recession of the Earth's crust by earth tides and derived a tentative formula relating these fluctuations to earth tides. *George* and *Romberg* [1951] presented data to show the relationship of changes in gravity and atmospheric pressure with fluctuations in artesian pressure near Fort Stockton, Tex.

In the course of ground-water investigations at Oak Ridge, Tenn., made by the Geological Survey at the request of the Atomic Energy Commission, recording gages to obtain continuous records of water-level fluctuations were installed on ten wells drilled into the Chickamauga limestone. In all these wells fluctuations of tidal period have been observed. In one well, referred to as Well 3, the fluctuations were especially pronounced. This Well is 250 ft deep, located 84°20′ W, and 35°55′ N. The Well is about 300 mi from the nearest point on the Atlantic ocean and about 400 mi from the Gulf of Mexico.

The Chickamauga limestone, in which Well 3 is drilled, is a shaly limestone which at this locality dips to the southeast at an angle of about 35°. The porosity and permeability of the rock, which are quite low, are due to bedding-plane openings and joints that have been slightly enlarged by solution. The residual clay soil that overlies bedrock is thin and permeable. Water-level measurements in Well 3 and a number of other wells in its vicinity show that the surface of the ground-water body conforms generally with the land surface. Depths to water range from a few feet to less than 20 ft below land surface and the water levels rise rapidly after rain.

The upper curve in Figure 1 shows the fluctuations of water level in Well 3 from August 19 to September 3, 1952 as recorded by the gage. This curve shows the occurrence of approximately two daily cycles of water-level fluctuations which come about 50 minutes later each day. The minima on the curve coincide in general with the transit of the Moon at upper and lower culmination. The range of fluctuation is greatest at the periods of new and full moon, ranging up to 0.3 ft, and smallest at the periods at the first and third quarters. These characteristics indicate that the approximately semidiurnal fluctuations of water levels are the result of earth tides produced by the attraction of the Moon and the Sun.

In the previously cited references to tidal phenomena observed in inland bore holes, the aquifers described were artesian and the water levels fluctuated with changes in barometric pressure. To determine if water levels in the Chickamauga limestone were affected by changes in atmospheric pressure the lower curve in Figure 1 showing the barometric pressure at a point 1.5 mi north of the Well as recorded by a microbarograph reading to 0.01 inch of mercury was plotted. The barometric graph is inverted and is expressed in feet of water. The amount of rain that fell during the period at a rain gage 1.5 mi north of the Well is shown by bars at the bottom of the figure. Comparison of the curves does not indicate any close correlation of fluctuations of the water level in the Well with changes in atmospheric pressure, although the large amplitude of the tidal fluctuations and the changes in water level due to recharge from rainfall obscure the analysis.

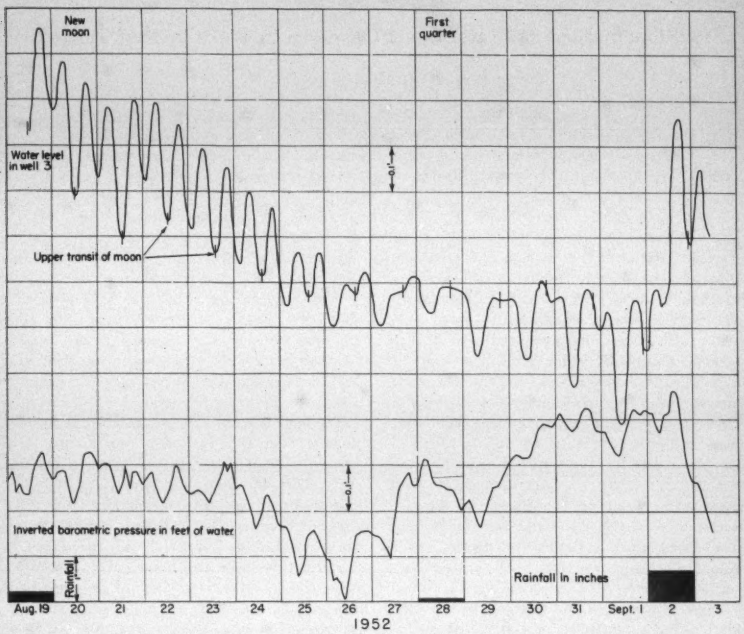

FIG. 1 – Water level in Well 3, inverted barometric pressure, and rainfall, August–September, 1952

Continuous records of fluctuations in artesian pressure in several wells completed in unconsolidated sand of Tertiary age in western Tennessee and in a well completed in the Knox dolomite of Cambrian and Ordovician age in central Tennessee show semidiurnal fluctuations apparently produced by tidal forces. As such fluctuations in water level have been observed in aquifers that are quite diverse in hydrologic properties, it would seem possible that fluctuations in ground-water levels caused by the direct action of the moon and the sun occur more generally than is commonly believed.

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Potential Value of Ground-Water Data

CARROLL F. MERRIAM

Abstract—Programs of observation of the natural fluctuations of ground water covering an extensive area where there is no continuous aquifer are discouraging for the reason that readings must be made for a considerable period of time before they begin to have meaning. The results are not directly translated into quantitative data in the manner that streamflow records are. Consequently to appreciate the potential value of this work it is necessary to have some perspective of the possible future significance. Otherwise opportunities to gather much needed basic hydrologic data may be lost.

Papers by the same author describing the method of analysis and the practical application in forecasting assured river flow have appeared in previous *Transactions* of the American Geophysical Union. This paper deals primarily with the precautions believed to be essential in maintaining the high standard of consistency in order to make the effort expended on observation of greatest use in the future.

Foreword—In his oral presentation the author departed from the prepared text in order to pay high tribute to the influence of O. E. Meinzer and N. C. Grover, prominent figures in the early history of the Section of Hydrology. He described the circumstances leading to the inception in Pennsylvania, of the first state-wide program of ground-water observations, and recalled that the program was stimulated not in response to known distressing lowering of ground-water levels, resulting from over pumping, but as a purely scientific venture without immediate prospect of useful results. This venture was especially significant because the known variations in topography and geologic conditions throughout the State precluded the existence of any single aquifer of great areal extent. The wisdom of Meinzer's foresight in encouraging such an observational program is amply demonstrated in the following paper.

In any well-considered scientific program there should always be thought for the future, particularly with respect to the new uses and applications which could possibly develop. This is important from the point of view not only of making provisions for the needs which may arise, but also of bolstering the morale of personnel engaged in the apparently humdrum collection of data without being able to see the picture as a whole, and the real importance of the work to which they are contributing.

The field of ground-water observations is particularly discouraging for the reason that the data taken by themselves may have very little value or apparent significance. It is only after years of painstaking recording that correlations can be established by which the work takes on meaning leading to useful results. I am in an excellent position to appreciate this since I saw the beginning of the first state-wide program of observation started by the U. S. Geological Survey. I saw the data accumulate for years as seemingly just so much spoiled paper. Then at the darkest hour the light began to dawn and gradually the way became clear ahead. In spite of the fact that ground-water storage has relatively little effect on the flow of the Susquehanna, the time of the year when it does exert a controlling influence coincides with the period of high incremental value of water so that the results though disappointing to the hydrologist become important to those who must estimate the availability of hydro-electric capacity. The system which has been in operation for a number of years has been reported in previous *Transactions* and elsewhere [Merriam, 1942, 1945, 1948, 1951], and has been reduced to routine.

Our concern for the future lies in two directions, first the preservation of standards so that the relationship curves will not be likely to need frequent revision, and second to investigate what further benefits may be derived not only from the point of view of industry but for the public in general.

Preservation of standards demands that there shall be a consistency of observation so that a given value one year will mean as nearly as possible exactly the same ground-water condition many years later. This sounds simple but as in all hydrologic observations it is difficult to attain. An individual well may be measured precisely in the same manner year in and year out, but it cannot be depended that this well will be averaged with exactly the same combination of other wells for any length of time. New wells will be added which should not be neglected simply because they were not in the original combination, and unfortunately old wells have a provoking habit of dropping out

for one reason or another. Furthermore, the observation wells, although selected to be situated as far as possible from artificial disturbances, could possibly suffer from excess water use in the vicinity.

The first safeguard is of course numbers, and for that reason the program should be expanded to take in as many wells as possible with funds available so that the average will be less subject to change resulting from freak readings, omitted readings, or the loss of seasoned wells. Numbers alone cannot be depended upon to stabilize the average and so means must be found by which all of the readings can be reduced to a common denominator, as is done by the rating curves described by the author [*Merriam*, 1942]. Here again vigilance must be exercised for fear that a well supposed to be abandoned and thus to respond only to natural fluctuations in ground-water level should happen to become used to the extent that it no longer would give true readings, or possibly be affected by pumped wells in the vicinity.

To provide proper assurance against mishap an annual audit is made in which the original data as reported are all plotted against the current or preliminary estimate of ground-water index which had been made each week throughout the year. The purpose is to see if by chance the individual points are falling so far away from the rating curves previously developed as to arouse suspicion. There is of course considerable spread in the points caused by the fact that ground-water conditions may vary widely in different parts of the entire drainage basin of 27,000 sq mi. Nevertheless if the trend should appear to be so unlike the rating curve and should persist over a considerable period of time that the difference could not be accounted for by normal accidental variations, then it would be necessary to modify the curve in the light of the new data. In some cases such a plot has detected mistakes in reporting, confusion as to the reference mark and other inconveniences which if undetected would detract from the value of the record.

In most cases no change is made in the rating curve and after a few spot checks, the readings as converted to the common scale are simply copied from the record book. In the few cases where it is felt that revision of the rating curve is advisable, a new curve is drawn and used to derive a new set of converted readings.

At this point a still further check is made, a chronological plot by weeks for each well after conversion to the common denominator. Each one is plotted on a separate sheet of thin paper so that it may be compared against a corresponding plot of the weekly index. By plotting the latter in ink so that it can be distinctly seen through the thin paper, it is easy to see to what extent any particular well follows the general trend of the group. This is very handy in picking out freak individual reports which may be caused by local storms but which may also be caused by blunders in reading. It will also pick out periods where for some reason or other the well record just 'goes haywire.' From the geological point of view these abnormal conditions may be most interesting, but extremely doubtful in contributing to the knowledge of the average ground-water level throughout the valley. Although a relatively small percentage of all readings are eliminated in this way, there is undoubtedly an improvement from disregarding them.

Displayed in Figure 1 are the chronological plots of water-level data for the calendar years 1953 and 1954, for observation wells in the Susquehanna Basin. The observations have been reduced to a common vertical scale, termed ground-water index, by means of the individual well rating curves. The plots are offset vertically to avoid interference and arranged in order of excellence with respect to conformity with the general average and continuity. The plots demonstrate that when reduced by application of established rating curves ground-water observations at widely diverse portions of the basin do follow a distinct pattern.

The principal advantage of the chronological plot is to get a better idea of the relative values of the wells as being indicative of the general average. The plots for some wells tend to wander far from the inked pattern with which they are compared, whereas others particularly in the part of the vallery which was formerly glaciated follow surprisingly well. Based on this comparison the weights used in the averaging are revised.

When this is done the calculation of the weekly index values is repeated, the results differing from those calculated currently because of three factors: (1) some of the rating curves may be slightly altered; (2) the weights used are generally different from those used formerly; and (3) data from New York State, for which there is as yet no provision for current reporting, are available at the end of the year but not in time for the regular forecast. This is unfortunate because it is the New York wells which are found to give as a rule the most consistent results. Nevertheless the surprising thing is that in spite of these changes, and the delay in receiving most of the data from New York, the change as compared with the weekly estimates throughout the year is relatively small. In other words, the annual audit is a refinement, an assurance against gross mistakes entering into the

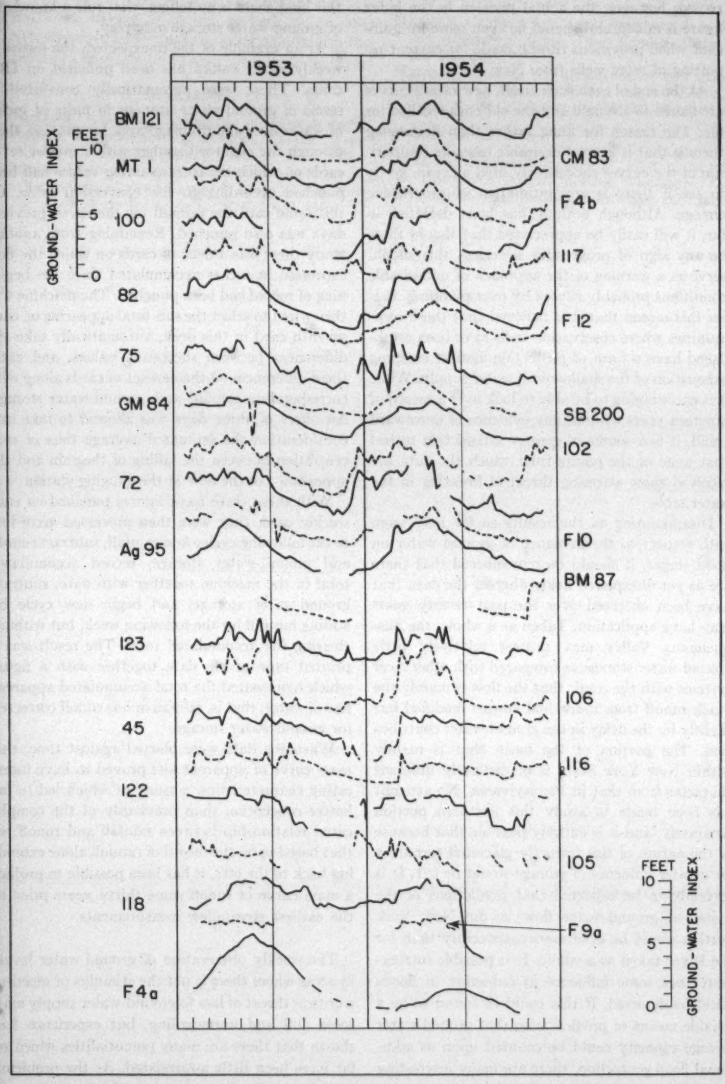

FIG. 1 – Weekly observation of ground-water elevations in the Susquehanna Basin during the calendar years 1953 and 1954

record; however, the actual revision in the index figure is minor, and should be even more insignificant when provisions can be made for current reporting of more wells from New York.

At the end of each such audit, new rating curves are issued to the field and the old ones recalled for file. The reason for filing rather than destroying them is that it is most desirable to make comparison of the curves successively used as years go by to see if there is any intimation of progressive change. Although nothing has been detected so far, it will easily be appreciated that should there be any sign of progressive lowering, this should serve as a warning of the approach of undesirable conditions probably caused by over pumping. It is for this reason that it is believed that those communities where observation wells have been established have a form of protection against creeping exhaustion of the shallow-well water supply. While it is encouraging to be able to look over a record of nineteen years without any evidence of downward trend, it is a source of greater satisfaction to feel that none of the points from which the data are received show alarming threat of lowering in the water table.

Disappointing as the results so far may seem with respect to the influence of ground water on flood stages, it should be remembered that there are as yet unexplored fields wherein the data that have been observed over the past twenty years may have application. Taken as a whole, the Susquehanna Valley may possess relatively little ground-water storage as compared with other river systems with the result that the flow is mainly the quick runoff from individual storms modified but slightly by the delay in the ground-water contribution. The portion of the basin that is mainly within New York State is of distinctly different character from that in Pennsylvania. No attempt has been made to study this northern portion separately, and it is entirely possible that because of the nature of this formerly glaciated terrain, a far greater influence of storage would be felt. It is certainly to be expected that predictions of the sustained ground-water flow in the New York portion would be even more satisfactory than for the River taken as a whole. It is possible furthermore that some influence in reduction in floods could be detected. If this could be found to be a reliable means of prediction so that ground-water storage capacity could be counted upon as additional flood protection, there are many interesting possibilities for modifying the rule curves at combined flood and storage reservoirs. In matters of this kind there is no telling what role a knowledge of ground-water storage may play.

As an example of the unexpected, the record of weekly index values has been punched on IBM cards. These were automatically converted to terms of ground-water storage in units of inches of water over the drainage area by running them through the collator together with a master set of cards on which the corresponding values had been punched according to the conversion table. On this same card the rainfall for the seven previous days was also punched. Remaining from another study there was a deck of cards on which the flow expressed in inches accumulated since the beginning of record had been punched. The machine was then wired to select the sub-total appearing on each seventh card in this deck, automatically take the differences between successive values, and enter these differences on the new set of cards along with corresponding rainfall and ground-water storage. An offset of three days was allowed to take into consideration the estimated average time of concentration between the falling of the rain and the appearance of the flow at the gauging station.

With these three basic figures punched on each weekly card, they were then processed according to the following cycle: Add rainfall, subtract runoff, add ground-water storage, record accumulated total in the machine together with date, subtract ground-water storage, and begin new cycle by adding rainfall for the following week, but without clearing the accumulated total. The result was a printed tape giving date together with a figure which represented the total accumulated apparent loss of water, that is, rainfall minus runoff corrected for ground-water storage.

When the data were plotted against time, this mass curve of apparent loss proved to have interesting characteristics, a study of which led to far better conception than previously of the complicated relationship between rainfall and runoff, so that based upon the record of rainfall alone extending back to the 60's, it has been possible to project a mass curve of runoff some thirty years prior to the earliest streamflow measurements.

The weekly observation of ground-water levels in areas where there is not the stimulus of meeting a critical threat of loss to ground-water supply may seem dull and unrewarding, but experience has shown that there are many potentialities which so far have been little appreciated. As the problems of understanding water resources become more and more intricate, there is little doubt as to the future

worth of having observed ground water consistently over many years in order to establish the necessary background to give meaning to the data.

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On Estimating Streamflow into a Tidal Estuary

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Abstract—Because standard stream-gaging methods cannot be applied to measure streamflow in a tidal estuary where currents reverse direction with each tidal cycle, other methods are required. Continuous velocity traverses across a section are satisfactory, but this method is laborious and costly. A method for estimating streamflow is described based upon continuous salinity recorder data, tidal data, and current tables. These data, combined with particular correction factors to make the information applicable to an entire channel cross-section, permit streamflow estimates to be prepared rapidly. To illustrate the procedure, streamflows from the Sacramento - San Joaquin Valley, California, entering San Francisco Bay are computed. Errors, applications, and limitations of the method are discussed.

Introduction—A tidal estuary may be defined as a coastal body of water connecting fresh- and salt-water sources and containing salinities intermediate between the two sources. Streamflow in an estuary reverses its direction periodically in response to tidal action, so that ordinary methods of measuring streamflow are unsatisfactory. The method of estimating streamflow from a stage-discharge relationship is not applicable because the direction and magnitude of the flow is not a unique function of stage. Another method is based on a hydrologic equilibrium between inflows and outflows tributary to the estuary. Its application, however, is often limited because the data for some of the elements involved in an equilibrium analysis are only approximate. A third method involves direct measurement of the instantaneous velocity. The moving-boat technique developed by *Ingerson* [1955] for this purpose provides accurate values, but its continued use would prove costly.

It is the purpose of this paper to describe a method for estimating streamflow into a tidal estuary based upon inexpensively obtained or readily available data, to illustrate this method with an example, and to discuss its applications and limitations.

An excellent summary of the interrelations of streamflow, tides, and salinity in estuaries has been prepared by *Keighton* [1954]. Other recent contributions by *Lindner* [1953] on salinity intrusion and by *Simmons* [1955] on river flow into estuaries are pertinent to the present discussion.

Outline of method—To apply this method a channel section perpendicular to the mean flow direction is selected. It should preferably be located in a straight and narrow reach of the estuary. The data required include published tide and current tables, hydrographic maps, and a continuous salinity record. The last may be obtained from a salinity recorder. One recorder successfully used in California [U. S. Bureau of Reclamation] consists of a self-balancing Wheatstone bridge, one leg of which is a test cell that is immersed in the stream channel and another is immersed in a standard cell. The other legs are a fixed and a variable resistor. The unbalance voltage in the bridge caused by changing water salinities is transmitted to a moving pen arm which furnishes a continuous record of the water salinity. Calibrations are performed by measuring salinities of a series of prepared standard solutions.

Two assumptions are necessary to apply this method. These are that the ocean and river waters in the vicinity of the selected section are well mixed, and that channel storage decreases upstream from the section. The first invalidates the method's application in estuaries containing salt-water density currents, while the second voids estuaries opening into larger water bodies upstream.

The flow through a channel section perpendicular to the flow direction consists of a certain per cent of river water. The river water flowing may be assumed to occupy a fraction A_f of the total channel area A, while sea water occupies A_s. For a total flow Q with a mean channel velocity V,

$$Q = Q_f + Q_s = A_f V + A_s V$$

where Q_f and Q_s represent the fresh-water and salt-water flows, respectively. If F is the fraction of the section occupied by fresh water

$$F = A_f/A$$

and

$$Q_f = FAV \qquad (1)$$

The total cross-sectional area A can be computed from soundings or hydrographic charts. It will vary with tide stage. It is proposed to compute V from published values in current tables. The fraction F can be expressed as a function of the salinity con-

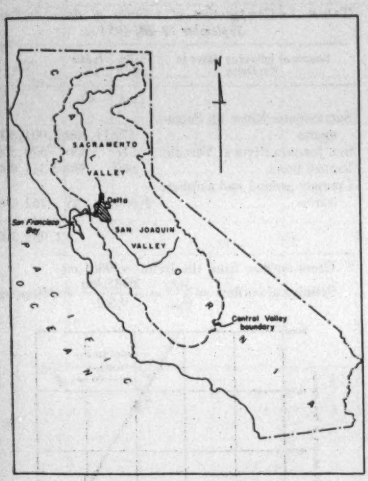

FIG. 1 – Location map of San Francisco Bay and Central Valley, California

centrations of fresh and salt waters sources and that of the section. Letting the salinity of the section S consist of a mixture of that from the fresh-water source S_f and of that from the ocean S_s, then for a volume of unit width at the section

$$SA = S_f A_f + S_s A_s$$

Inserting the expression for F from above gives

$$F = \frac{S_s - S}{S_s - S_f} \qquad (2)$$

This indicates that as S approaches S_s, F approaches zero; conversely, F approaches one for S approaching S_f. As F, A, and V are functions of time, Q_f must be computed for instantaneous conditions at short time intervals.

Application to outflow from the Sacramento-San Joaquin Delta, California—The Sacramento and the San Joaquin Rivers drain the Central Valley of California, intermingle in the Sacramento - San Joaquin Delta, and discharge into San Francisco Bay (Fig. 1). The streamflow from these two major rivers and from other minor contributing streams is a major source of water supply for irrigation, municipal, and industrial needs. Within the Delta, however, sea-water encroachment from the Pacific Ocean caused by tidal action contaminates this supply, especially during the summer low-flow period. The propagation of salinity is known to be

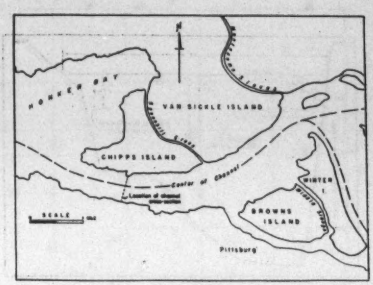

FIG. 2 – Location map of Chipps Island channel cross-section

some inverse function of the seaward streamflow. *Glover* [1955] has formulated a procedure for computing salinity intrusion from streamflow based upon an analysis of previous records.

To prevent sea water from entering the Delta and to create a fresh-water reservoir of the Delta, proposals have been made to construct a barrier across upper San Francisco Bay. These have led to several engineering investigations of the technical and economic feasibility of such a barrier [*Young*, 1929; *Matthew*, 1931ab; *California Water Project Authority*, 1955b]. One of the important factors required in these barrier studies was an accurate estimate of the fresh-water inflow, not only for feasibility but also for design and operation of a barrier. The latest of these studies served as an incentive to apply the above method to the problem of estimating streamflow into San Francisco Bay.

For the purpose of estimating the fresh-water streamflow, the main channel section at Chipps Island, located at the lower end of the Delta and shown in Figure 2, was selected. This site was particularly desirable, as flows were measured here by the Water Project Authority of California in 1954 and thus provided a unique opportunity to compare computed and measured flows. It should be noted that in addition to the main channel there are two small natural channels, Spoonbill Creek and the Montezuma Slough, that connect the waters of the Delta and the Bay. According to measurements made by the Water Project Authority, however, the flow through these two channels is negligibly small.

The selected channel cross section for study is shown in Figure 3. By planimetry the relation between channel area and tidal stage shown by Figure 4 was determined. Tidal stages may be obtained from *Tide Tables* [*U. S. Dept. of Com-*

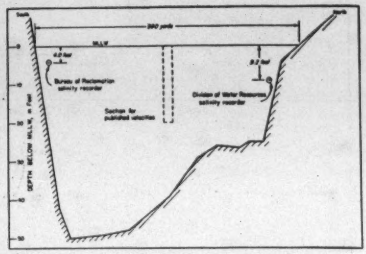
MLLW
Bureau of Reclamation salinity recorder
Division of Water Resources salinity recorder
Section for published velocities
DEPTH BELOW MLLW, in Feet

FIG. 3 – Channel section at Chipps Island site

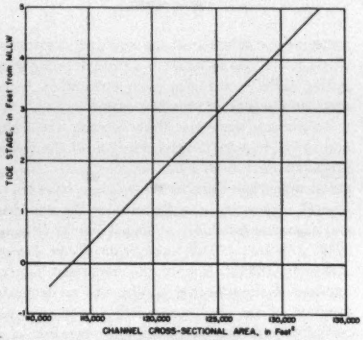

FIG. 4 – Relation of tide stage to channel cross-sectional area at Chipps Island site

merce], but a more accurate record may be obtained from an automatic stage recorder. In the present study a tide record was obtained and furnished by the Water Project Authority.

The salinity of sea water off the coast from the Golden Gate was reported as 34,040 ppm total dissolved solids by *Sumner* and others [1914] and as 33,394 ppm by *Matthew* [1931a]. Based on these consistent results, a salinity of 34,000 ppm total dissolved solids was assumed for the ocean.

The river waters of the Sacramento and the San Joaquin Rivers passing through the Delta, pick up return irrigation flow and ground water. The river water salinity, consequently, is a weighted average of its source salinities. For the period during which the streamflow is to be computed, September 12–26, 1954, the Water Project Authority has evaluated the inflows [*California Dept. of Public Works*] and salinities [*MacRostie*, 1955] of the river water based on measurements presented in Table 1. The large discrepancy between total

TABLE 1 – *Computation of salinity of delta outflow, September 12–26, 1954*

Source of inflowing water to the Delta	Salinity S	Inflow Q_{in}	SQ_{in}
	ppm	cfs	
Sacramento River at Sacramento	179	11,200	2,004,800
San Joaquin River at Vernalis	570	650	370,500
Return flows	600	580	348,000
Connate ground and sulphate water	4,030	65	262,000
			2,985,300

Gross outflow from the Delta = 9661 cfs.

Salinity of outflow $= \frac{SQ_{in}}{Q_{out}} = \frac{2,985,300}{9,661} = 310$ ppm.

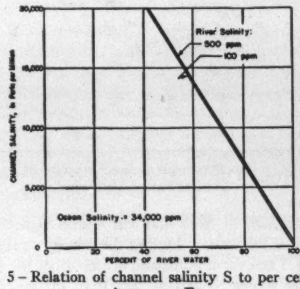

FIG. 5 – Relation of channel salinity S to per cent of river water F

inflow and outflow is caused by evapotranspiration losses within the Delta. With S_s and S_f determined, a relation between F and S is defined by (2). This is expressed graphically in Figure 5 for two values for S_f.

The mean channel salinity S at the Chipps Island site was obtained by calibrating the point salinity measured at the recorder with actual measurements of the channel salinity. At this site, salinity recorders had been installed, one near the north shore by the Division of Water Resources and the other by the U. S. Bureau of Reclamation near the south shore (see Fig. 3). Mean channel salinity measurements by the Water Project Authority were made during this period using the moving-boat technique [*Ingerson*, 1955]. Incidentally, because of the wide interest expressed in these measurements, all of the basic data have been published [*California Water Project Authority*, 1955a]. In Figure 6 are plotted hourly salinities of the Division of Water Resources recorder against corresponding channel measurements for five arbitrarily selected tidal cycles (each cycle occupies about 25 hours) during the measurement period.

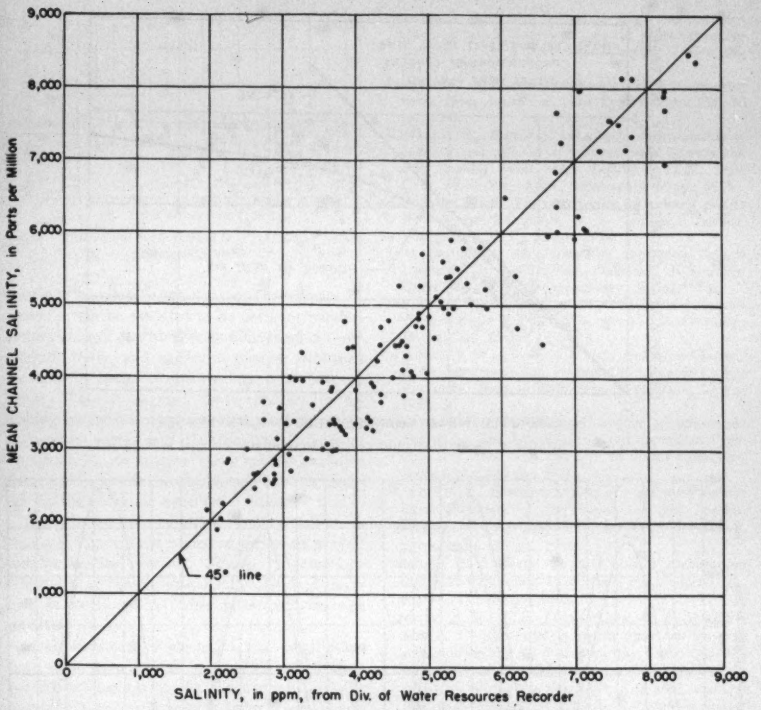

FIG. 6 – Relation of mean channel salinity to recorder salinity

The points are limited to a narrow band along the 45° line. For this reason the recorder salinities were taken as representative of the entire channel. Separate graphs for ebb and flood phases were also plotted, but they showed no apparent differences.

Current Tables [*U. S. Dept. of Commerce*], published annually by the U. S. Coast and Geodetic Survey, were used to estimate channel velocities. These published velocities are intended for navigation purposes and are applicable only for a 20-foot depth at mid-channel. In order to use the published velocities, it is necessary to correlate them to mean channel velocities. In examining concurrent published and measured velocities it was noted that small irregular discrepancies occurred as to the time of slack water. Thus, to eliminate introducing these errors in a graphical plot, velocities were selected at equal fractions of the time interval between two slack waters. The fractions 0.1, 0.3, 0.5, 0.7, and 0.9 were chosen to represent the range of velocities. These corresponding fractions for the entire 14 days of measurement are plotted on Figure 7. The curve best fitting the points was used to relate computed mean channel velocities from *Current Tables* to observed mean channel velocities obtained from *California Water Project Authority* [1955a].

Instantaneous streamflows for the period September 12–26, 1955 were computed from (1) at half-hour intervals to adequately define variations induced by tidal fluctuations.

Results and discussion—A hydrograph of computed instantaneous streamflow for two days of the period is plotted as Figure 8. On the same graph is plotted measured total flow. These represent different flow quantities, and hence are not directly comparable. The net streamflow passing

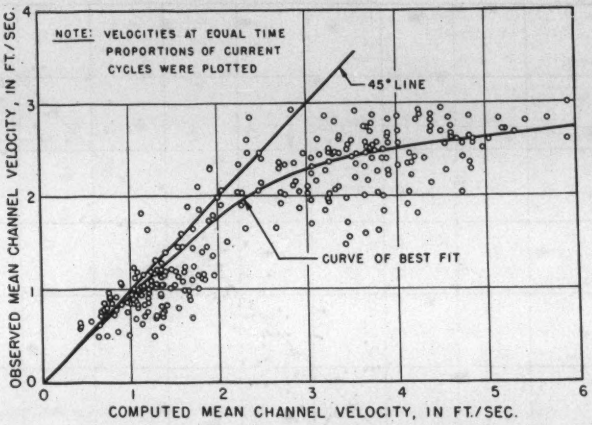

FIG. 7 – Relation of observed channel velocity to computed channel velocity

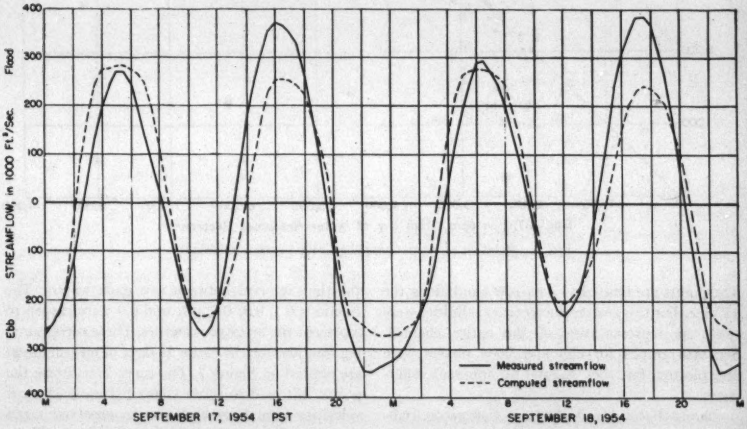

FIG. 8 – Hydrographs of measured total flow and computed streamflow

through the section during each tidal cycle, obtained by algebraically summing the flow volumes, is plotted in Figure 9. From this the mean flow for the 14-day period was found to be 2775 cfs. The measured Delta outflow for the same period was reported by *Kabakov* [1955] to be 7353 cfs. The failure of the computational method in this case can be attributed to the violation of the second assumption, stated earlier. Upstream from the channel section, the Delta serves as a vast temporary storage reservoir. Salinities within the Delta vary on a seasonal basis so that salinities of river water entering it may differ widely from those of outflow water. Then too, any problem seeking to find a small difference between very large quantities, as is here the case, can seldom provide an accurate result.

The accuracy of the method outlined herein is limited by the errors of the factors F, A, and V. Providing the basic assumptions are met and providing reasonably reliable salinity and hydrographic data are available, the first two factors

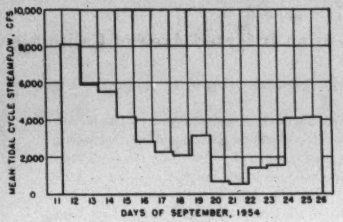

FIG. 9 – Mean tidal cycle stream flow for 14-day period of September 1954

need not introduce serious errors. The velocity V, however, can be expected to be the least reliable. Inaccuracies of published data, differences in times of slack water, and scatter in relating published currents to mean channel values contribute to errors. The advantages of the method are its furnishing continuous estimates of streamflow rather than mean values over time periods, its ease of computation, its reliance upon readily available data, and its low cost in comparison to other methods for obtaining the same information.

It is believed that the wide streamflow variations shown in Figure 9 are related to variations in tidal amplitudes and periods. Future investigations which aid in defining this relationship will make notable contributions to this important hydrologic problem.

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Discharge of Tile Drainage Systems in an Irrigated Area of California

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Abstract—Measurements of discharge from the drains in the Coachella Valley of California have been plotted, and a simple equation has been developed, to give maximum discharge in terms of drainage area or length of tile. It has not been possible as yet to relate the coefficients or exponents involved to differences in soil characteristics or irrigation practices, but as more information is developed this may be possible.

Good data on which to base the design capacity of tile drains in irrigated areas have been lacking. The 'drainage coefficient' used in humid areas is not applicable, and the ponded condition, which would permit rational calculation of discharge (*Kirkham*, 1949) is not reached. The information here developed is presented as a first step towards solution of the problem.

The Coachella Valley of California is a desert area with average annual rainfall of less than three inches. As a part of the Boulder Canyon Project, water has been imported into the Valley since 1948 through a branch of the All-American Canal. Prior to that time essentially no sub-surface drainage was required for the scattered farm land irrigated with local ground water. Since then, as a result of application of irrigation water in excess of crop needs [*Reger* and others, 1950], the water table has risen and drainage measures have become necessary for about 15,000 acres of irrigated land. Great variations in water application were found, which may be due in part to differences in the water requirements of the various crops. There is considerable diversification of crops varying from citrus, dates, and alfalfa which require water the year around, to field crops such as cotton which is irrigated principally in summer, to grapes which are irrigated principally in spring and summer, and to vegetables which are grown in winter, spring, and fall. The predominantly sandy soils generally have medium to low moisture retention properties, but considerable stratification exists which alters the moisture regime. At the outset, there was no reliable criterion available to use in designing tile systems.

The study reported here was undertaken as a part of a cooperative drainage and salinity project of the Coachella Valley County Water District, the U. S. Salinity Laboratory, the U. S. Bureau of Reclamation, and the University of California. Work was started in 1945 and has been in progress since. Initially, conservative arbitrary criteria were used in design, and, so far as possible, flows from the systems have been metered from time to time.

An attempt was made to select a period of about two weeks during each quarter of the year when the irrigation of certain crops appeared to be maximum, and to make daily measurements at as many tile outlets as possible. Several methods of metering were used. In each case the method best adapted to the site, and which gave the most accurate results, was used. Some measurements were volumetric, some were made with a small current meter, some with a weir, etc. Accuracy was quite adequate for the purpose. In order to obtain records from larger areas than provided by those obtained at the individual outlets, essentially simultaneous readings from a number of systems were combined. Values of tile discharge are plotted as a function of total tile length in Figure 1.

The dashed line in Figure 1 is an approximate upper boundary for the measured values, and may be represented by the empirical equation

$$q = 50\, L^{-0.25} \qquad (1)$$

where q = maximum discharge in gallons per minute per thousand feet of tile, and L = length of tile in thousands of feet.

Expressed on an area basis, and using an average of 162.5 ft of tile per acre, this equation becomes

$$Q = 0.028\, a^{0.75} \qquad (2)$$

where Q = maximum flow in cfs, and a = area in acres.

Probably these equations are somewhat conservative for reasons that are discussed below, but they have proven to be useful in their present form. It is anticipated that they will be improved or refined as additional tile is installed and as additional records are obtained.

Some of the factors involved in the design and functioning of tile drains, which indicate the design criterion to be conservative, are as follows:

(1) The particularly high records, those significantly above the curve of Figure 1, are for tile systems in the coarse sand of old buried stream channels. Such conditions are readily recognized,

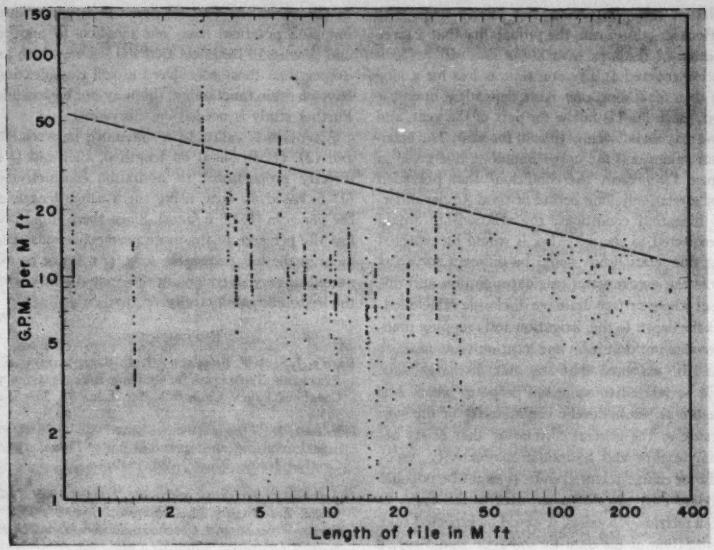

FIG. 1 – Records of discharge of tile lines in Coachella Valley, California, per thousand feet of line, plotted against length of system in thousands of feet; the dashed line represents the equation developed for maximum design flow

and provisions can be made easily for greater capacity by using a higher coefficient.

(2) There is evidence that tile drains can survive infrequent flows in excess of capacity without damage. In a number of instances, tile systems have been subjected to a high pressure head due to root plugging. In one instance, some roots broke loose upstream, moved downstream with the flow and suddenly became lodged at a connection with a District main outlet drain. Water boiled up to the surface over a considerable distance. When the plug was removed, approximately 100 feet of the line was uncovered and not a single section of tile was cracked or displaced. This has been true with all other plugged lines.

(3) Those installations where maximum discharge does exceed design flows are those where soils are extremely permeable. Actual peak flow rates will initially be very high, but will drop off rapidly. Effect of restricted tile capacity will simply be to lengthen the duration of the relatively short peaks. The design would still appear to be conservative.

(4) The maximum drainage discharge rates measured may reflect the poor irrigation practices existing in parts of the Valley. For a number of reasons the average irrigation efficiency is low. With more lands being brought under irrigation, and with irrigation water becoming more valuable, it is reasonable to expect some future increases in irrigation efficiency. This will result in a decrease in maximum drainage discharge.

(5) There has not been any evidence in Coachella Valley to substantiate the belief that the flow into drain tile increases with age of line. The permeability of the soil is such that there has been no need for small water courses or channels to be developed in order for drainage water to enter into the tile.

The decrease of inflow per unit length of tile drains as the total length of tile line increases is related to the irrigation frequency and areal distribution of water on the various farms in the area. If all of the area adjoining a tile line were irrigated at one time, it would be expected that the rate of inflow per unit length of tile would be independent of the total length of tile drain. Because of the fact that water is applied at different locations at

different times on various size border strips with various lengths of run, the probability that a given fraction of the area over a tile line will be completely covered at any one time is less for a long tile than for a short one. Also, dependent upon the crop, much land is fallow for part of the year, and some may be fallow any time of the year. The maximum values and the upper bounding line given in Figure 1 represent the conditions that prevailed over a relatively long period of time. Under different irrigation conditions, the relationship would be expected to change. Also, it would be expected that this relationship would be different for areas where the excess water originates as rain and different where surface drainage discharge is included.

If the depth to tile, irrigation and cropping practices were uniform from one location to another, it would be expected that the unit discharge data could be related to some soil property which is a measure of the hydraulic conductivity of the soil. Because of the general correlation that exists between texture and hydraulic conductivity, especially for coarse-textured soils, it might be possible to relate unit tile discharge rates to soil type. If such a relationship exists, it would be expected that classification of the data by soil type would result in a family of curves with the curves for the more permeable soils being above those for the less permeable soils. Whether or not such a correlation might be possible still remains to be seen. Because of the variations that do occur in irrigation and cropping practices from one location to another and because of the effect that soil layers, which are deeper than those considered in soil classification, have on drain functioning, this may not be possible. Further study is needed on this point.

Attention is called to a difference between (1) and (2). (1) Is based on length of tile, and Q is directly proportional to hydraulic conductivity. (2) Is based on area, using the average length of tile per acre (162.5 ft/acre). Since there should be less tile per acre in the more permeable soils, and more in the less permeable soils, Q will not be expected to vary so widely, nor to vary directly with the hydraulic conductivity.

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The Effect of Elastic Intrusions upon a Gravitational Stress

H. S. HEAPS

Abstract—Formulas are obtained for the state of stress within an elastic material subject to the force of gravity and containing intrusions of different elastic properties. It is assumed that the elastic properties of the intrusions do not differ greatly from those of the surrounding medium. The formulas are first expressed in a form that is independent of the specific shape of the intrusions. When the intrusions are distributed uniformly throughout the material the additional shearing stress at any place is inversely proportional to the fourth power of the spacing of the intrusions. Figures are included to show the effect of a single intrusion upon the shearing stress at distant points within the surrounding material. A further figure shows the distribution of shearing stress at points just outside a spherical intrusion. This stress is independent of the radius of the intrusion.

Introduction—Many problems relating to the mechanical behavior of the crust of the Earth involve an estimation of the distribution of stress within an elastic material under the influence of specified internal and external forces. In application of the mathematical theory of elasticity to such problems it is usually assumed that the material is homogeneous in that its elastic properties do not vary from point to point. While such an assumption is seldom true in the case of geological material it represents a useful approximation, but it does not provide for calculation of the internal stresses caused by the presence of soft or hard intrusions or by the occurrence of regions stressed elastically beyond the limit of validity of Hooke's law. The purpose of the present paper is to investigate theoretically the possible state of stress within a gravitationally stressed elastic material having elastic properties which vary slightly with position. An example of such material is a homogeneous host rock that contains inhomogeneities in the form of intrusions of different elastic properties. A further example is concrete in which the particles of aggregate are regarded as intrusions within a uniform surrounding medium [*Pickett*, 1956].

The effect of small spherical intrusions upon the elastic constants of otherwise homogeneous material has been considered by *Rehner* [1943], *Guth* [1945], and by *Dewey* [1945] who has also treated the case of non-rigid spherical intrusions [*Dewey*, 1947]. The effect of spherical cavities upon the elastic constants has been discussed by *Mackenzie* [1950] and by *Nabarro* [1940ab]. *Miyamoto* [1951] has investigated the stress distribution around a spheroidal cavity within material subject to torsion. *Robinson* [1951] has obtained the distribution of stress around an ellipsoidal elastic intrusion within an infinite material subject to a temperature increase while *Mindlin* and *Cooper* [1950] have solved the similar problem where the intrusion is a cylinder of elliptical cross section. The stresses in an elastic medium caused by the presence of a hot ellipsoidal or cylindrical intrusion have been obtained by *Mykelstad* [1942]. *Hardiman* [1954] has derived the stress distribution around an elliptical intrusion in a thin plate subject to a constant stress distribution at infinity. The influence of small spherical cavities or obstacles upon the velocity of propagation of elastic waves has been examined by *Satô* [1952, 1953].

The effect of an intrusion upon the stress at a neighboring point is dependent upon the shape of the intrusion, which in many geological problems cannot be ascertained specifically. It is thus desirable to seek results expressible in general terms independent of the precise shape of the inhomogeneities. However, such results cannot be expected to predict the effect of a particular intrusion at points close to its boundary.

The basis of the method of the present paper is the replacement of the intrusions by equivalent body forces given by (4) below. The derivation of this equation was presented in a previous paper [*Heaps*, 1955] and is summarised below.

Within an elastic material of elastic parameters λ and μ which vary with position the displacements u_1, u_2, and u_3 must satisfy the three equations

$$\mu\nabla^2 u_i + (\lambda + \mu)\,\partial\vartheta/\partial x_i + f_i + \vartheta\partial\lambda/\partial x_i + 2\sum_j e_{ij}\partial\mu/\partial x_j = 0 \quad (1)$$

where $e_{ij} = \frac{1}{2}(\partial u_i/\partial x_j + \partial u_j/\partial x_i)$, $\vartheta = e_{11} + e_{22} + e_{33}$, f_i are the components of external force acting upon unit volume of material, and ∇^2 denotes the differential operator $\partial^2/\partial x_1^2 + \partial^2/\partial x_2^2 + \partial^2/\partial x_3^2$.

If the elastic parameters λ and μ possess only a

small variation from constant values of λ_0 and μ_0 they may be written in the form

$$\lambda = \lambda_0 + l, \qquad \mu = \mu_0 + m \tag{2}$$

where l and m are functions of position such that at any place $(l/\lambda)^2 \ll 1$ and $(m/\mu)^2 \ll 1$. The displacements u_i may similarly be written in the form

$$u_i = v_i + w_i \tag{3}$$

where v_i is the solution of (1) when l and m are zero throughout the medium. Denote $\frac{1}{2}(\partial v_i/\partial v_j + \partial v_j/\partial x_i)$ by f_{ij} and $f_{11} + f_{22} + f_{33}$ by ϑ_0. Substitution of (2) and (3) into (1), and the neglect of second order terms, shows that the displacements w_i are equal to those which would result in homogeneous material of elastic constants λ_0 and μ_0 under the influence of a body force of components g_i per unit volume where

$$g_i = 2\sum_j \partial(mf_{ij})/\partial x_j + \partial(l\vartheta_0)/\partial x_i \tag{4}$$

Similarly the stress at a place of elastic parameters λ and μ is obtained by adding a correction term t_{ij} to the stress components s_{ij} that would result upon application of the known body and surface forces to material of elastic constants λ and μ. The values to be taken for λ and μ are the specific values at the point considered. The correction term is the stress resulting from application of the body force (4) to homogeneous material of elastic constants λ_0 and μ_0.

From the above remarks it follows that, in an elastic inhomogeneous medium having elastic parameters which exhibit only slight variation from constant values, the stress distribution may be calculated provided it is possible to calculate the stresses s_{ij} for homogeneous material under the same applied forces and boundary conditions and provided it is also possible to calculate the stresses t_{ij} for homogeneous material under the same boundary conditions, but with a body force given by (4). In many problems solution of the equations to determine the s_{ij} involves laborious numerical calculation. Exact solution for the t_{ij} is dependent upon the feasibility of setting up a coordinate system with respect to which the equivalent body force may be expressed in simple terms and with respect to which the equations of elasticity become separable.

Equivalent body force in material stressed by gravity—In the instance of a gravitationally stressed semi-infinite homogeneous medium below the plane $x_3 = -h$ and at rest at infinity the only non-zero stress components are

$$s_{11} = s_{22} = -\sigma_0(1 - \sigma_0)^{-1}w(x_3 + h) \tag{5a}$$

$$s_{33} = -w(x_3 + h) \tag{5b}$$

where w is the density of the material and σ_0 is Poisson's ratio. Then

$$v_3 = -\tfrac{1}{2}w(\lambda_0 + 2\mu_0)^{-1}(x_3 + h)^2$$

and the only non-zero f_{ij} is

$$f_{33} = -w(\lambda_0 + 2\mu_0)^{-1}(x_3 + h) = \vartheta_0.$$

The presence of spatial variations l and m in λ and μ is equivalent to a body force with components

$$g_1 = -w(\lambda_0 + 2\mu_0)^{-1}(x_3 + h)\partial l/\partial x_1 \tag{6a}$$

$$g_2 = -w(\lambda_0 + 2\mu_0)^{-1}(x_3 + h)\partial l/\partial x_2 \tag{6b}$$

$$g_3 = -w(\lambda_0 + 2\mu_0)^{-1} [l + 2m + (x_3 + h)(\partial/\partial x_3)(l + 2m)] \tag{6c}$$

At sufficiently small depths $x_3 + h$ the differentiated terms in (6) may be neglected and the inhomogeneities are equivalent to a vertical body force with the single component

$$g_3 = -w(\lambda_0 + 2\mu_0)^{-1}(l + 2m).$$

However, at sufficiently large depths the term $l + 2m$ may be neglected and the equivalent body force depends only upon the small scale variation of l and m. Consequently, a single intrusion of uniform material at a small depth below the surface gives rise to equivalent forces throughout its volume while at a greater depth the equivalent forces act over its surface of contact with the surrounding medium. Since a given volume possesses the least surface area when it has the shape of a sphere it follows that at a sufficient depth the overall effect of a number of spherical intrusions is less than if the same volume of intrusive material is distributed differently.

Formulas for the stresses caused by inhomogeneities—When an internal force of magnitude

$$8\pi\mu(\lambda + 2\mu)(\lambda + \mu)^{-1}$$

and direction parallel to the x_3 axis is applied to the point (y_1, y_2, y_3) within an unbounded elastic body it follows from the equations of *Love* [1944, p. 185] that the stress components at any other point (x_1, x_2, x_3) are

$$t_{11} = 2\mu^2(\lambda + \mu)^{-1}(x_3 - y_3)r^{-3} - 6\mu(x_1 - y_1)^2(x_3 - y_3)r^{-5} \tag{7a}$$

$$t_{22} = 2\mu^2(\lambda + \mu)^{-1}(x_3 - y_3)r^{-3} - 6\mu(x_2 - y_2)^2(x_3 - y_3)r^{-5} \tag{7b}$$

$$t_{22} = -2\mu^2(\lambda + \mu)^{-1}(x_2 - y_2)r^{-3} - 6\mu(x_2 - y_2)^3r^{-5} \quad (7c)$$

$$t_{23} = -2\mu^2(\lambda + \mu)^{-1}(x_2 - y_2)r^{-3} - 6\mu(x_2 - y_2)(x_3 - y_3)^2r^{-5} \quad (7d)$$

$$t_{13} = -2\mu^2(\lambda + \mu)^{-1}(x_1 - y_1)r^{-3} - 6\mu(x_1 - y_1)(x_3 - y_3)^2r^{-5} \quad (7e)$$

$$t_{12} = -6\mu(x_1 - y_1)(x_2 - y_2)(x_3 - y_3)r^{-5} \quad (7f)$$

where $r^2 = (x_1 - y_1)^2 + (x_2 - y_2)^2 + (x_3 - y_3)^2$.

By obvious permutation of subscripts the formulas (7) may be applied to determine the effect of an internal force that acts in either the x_1 or x_2 direction. Superposition of appropriate multiples leads to the effect of an internal point force of components given by (6) at a single point (y_1, y_2, y_3). Integration in y_1, y_2, and y_3 over the entire volume containing the intrusions leads to the stresses t_{ij} caused by their presence.

Consider the evaluation of the stress component t_{33} caused by the presence of a number of elastic intrusions each of finite volume. The right hand side of (7c) may be written in the form

$$2\mu(3\lambda + 4\mu)(\lambda + \mu)^{-1}(\partial/\partial x_3)(1/r) - 2\mu\partial^3 r/\partial x_3^3.$$

Thus, apart from the factor $8\pi\mu(\lambda + 2\mu)(\lambda + \mu)^{-1}$, the contribution of the force component (6c) to the stress component t_{33} is

$$t_{33}^{(3)} = -\frac{2w\mu(3\lambda + 4\mu)}{(\lambda + \mu)(\lambda + 2\mu)}(\partial/\partial x_3) \cdot \int(1/r)(\partial/\partial y_3)[(y_3 + h)(l + 2m)]\,dy + \frac{2w\mu}{(\lambda + 2\mu)}(\partial^3/\partial x_3^3) \cdot \int r(\partial/\partial y_3)[(y_3 + h)(l + 2m)]\,dy \quad (8)$$

in which the integration is over the entire volume of the intrusions. The superscript (3) is used to indicate that $t_{33}^{(3)}$ is the portion of t_{33} caused by a component of internal force parallel to the x_3 axis. More generally $t_{jk}^{(i)}$ may be used to designate the portion of t_{jk} caused by a component of internal force parallel to the x_i axis. The integrals in (8) may be integrated by parts with respect to y_3 over each intrusion. Since l and m are equal to zero just outside the boundary of each intrusion then

$$\int(1/r)(\partial/\partial y_3)[(y_3 + h)(l + 2m)]\,dy = -\int(y_3 + h)(l + 2m)(\partial/\partial y_3)(1/r)\,dy = (\partial/\partial x_3)\int(y_3 + h)(l + 2m)(1/r)\,dy = \tfrac{1}{2}h(\partial/\partial x_3)\nabla^2(L + 2M) \quad (9)$$

with the functions L and M defined by

$$\left.\begin{aligned} hL &= \int(y_3 + h)lr\,dy \\ hM &= \int(y_3 + h)mr\,dy \end{aligned}\right\} \quad (10)$$

Similarly

$$\int r(\partial/\partial y_3)[(y_3 + h)(l + 2m)]\,dy = h(\partial/\partial x_3)(L + 2M) \quad (11)$$

Substitution of (9) and (11) into (8) shows that, apart from the factor $8\pi\mu(\lambda + 2\mu)(\lambda + \mu)^{-1}$, the contribution of the force component (6c) to the stress component t_{33} is

$$t_{33}^{(3)} = -\frac{wh\mu(3\lambda + 4\mu)}{(\lambda + \mu)(\lambda + 2\mu)}\frac{\partial^2}{\partial x_3^2}\nabla^2(L + 2M) + \frac{2wh\mu}{\lambda + 2\mu}\frac{\partial^4}{\partial x_3^4}(L + 2M) \quad (12a)$$

Likewise, the contribution of the force component (6a) is

$$t_{33}^{(1)} = -\frac{wh\lambda\mu}{(\lambda + \mu)(\lambda + 2\mu)}\frac{\partial^2}{\partial x_1^2}\nabla^2 L + \frac{2wh\mu}{\lambda + 2\mu}\frac{\partial^4 L}{\partial x_3^2\partial x_1^2} \quad (12b)$$

with a similar expression for $t_{33}^{(2)}$ caused by the component (6b). Addition of $t_{33}^{(1)}$, $t_{33}^{(2)}$, and $t_{33}^{(3)}$, followed by multiplication by the factor

$$8\pi\mu(\lambda + 2\mu)(\lambda + \mu)^{-1},$$

leads to the total component t_{33}.

In a similar manner may be derived the following formulas to determine t_{11}

$$t_{11}^{(1)} = -\frac{wh\mu(3\lambda + 4\mu)}{(\lambda + \mu)(\lambda + 2\mu)}\frac{\partial^2}{\partial x_1^2}\nabla^2 L + \frac{2wh\mu}{\lambda + 2\mu}\frac{\partial^4 L}{\partial x_1^4} \quad (13a)$$

$$t_{11}^{(2)} = -\frac{wh\lambda\mu}{(\lambda + \mu)(\lambda + 2\mu)}\frac{\partial^2}{\partial x_2^2}\nabla^2 L + \frac{2wh\mu}{\lambda + 2\mu}\frac{\partial^4 L}{\partial x_1^2\partial x_2^2} \quad (13b)$$

$$t_{11}^{(3)} = -\frac{wh\lambda\mu}{(\lambda + \mu)(\lambda + 2\mu)}\frac{\partial^2}{\partial x_3^2}\nabla^2(L + 2M) + \frac{2wh\mu}{\lambda + 2\mu}\frac{\partial^4(L + 2M)}{\partial x_1^2\partial x_3^2} \quad (13c)$$

Interchange of the suffixes 1 and 2 in (13) provides formulas to determine t_{22}. The shear components t_{ij} may be deduced in a similar manner from (7def) and need not be listed here.

The derivation of (12) and (13) neglected the

surface condition of zero stress at $x_3 = -h$. The condition of zero shearing stress at $x_3 = -h$ may be satisfied by assuming that the space $x_3 < -h$ contains inhomogeneous material of elastic parameters $\lambda_0 - l(x_1, x_2, -x_3 - 2h)$ and $\mu_0 - m(x_1, x_2, -x_3 - 2h)$. Further addition of a suitable normal distribution of force along the surface $x_3 = -h$ then insures zero normal stress at the surface. However, the resultant effect of the surface upon the stress components of (12) and (13) is significant only at points sufficiently close to it.

Numerical values of shearing stress—The total stress at any point within the material surrounding the intrusions has components $s_{ij} + t_{ij}$ given by (5) and (12), etc. The principal stresses are the solutions s of

$$\begin{vmatrix} s_{11} + t_{11} - s & t_{12} & t_{13} \\ t_{21} & s_{22} + t_{22} - s & t_{23} \\ t_{31} & t_{32} & s_{33} + t_{33} - s \end{vmatrix} = 0 \quad (14)$$

Expansion of this determinant, with the neglect of second order products of the t_{ij}, shows that the principal stresses are $s_{ii} + t_{ii}$. The maximum shearing stress at any place is

$$\tfrac{1}{2}(s_{11} - s_{33} + t_{11} - t_{33}) = \tfrac{1}{2}(1 - 2\sigma)(1 - \sigma)^{-1}w(x_3 + h) + \tfrac{1}{2}(t_{11} - t_{33}) \quad (15)$$

Thus by (12) and (13) the presence of the intrusions increases the maximum shearing stress at any place by

$$\tfrac{1}{2}(t_{11} - t_{33}) = \frac{wh}{8\pi(\lambda + 2\mu)^2}\left\{\left(\frac{\partial^2}{\partial x_3^2} - \frac{\partial^2}{\partial x_1^2}\right)\left[\mu^2\nabla L - 2(\lambda + \mu)\frac{\partial^2 M}{\partial x_3^2}\right] + 2(\lambda + 2\mu)\frac{\partial^2}{\partial x_3^2}\nabla^2 M\right\} \quad (16)$$

In order to determine from (16) the effect of elastic intrusions upon the maximum shearing stress at any place it is first necessary to evaluate the integrals (10). In general the integration does not lead to results expressible in closed form. For the case of a uniform vertical force acting over an internal horizontal plane circular region the corresponding integrals have been expressed by *Dean*, *Parsons*, and *Sneddon* [1944] in terms of elliptic functions, but the necessary computation to obtain numerical values of the t_{ij} is lengthy for general position of the point (x_1, x_2, x_3). The present problem is further complicated by the fact that the equivalent body forces vary with depth and possess horizontal as well as vertical components. This is taken into account by (16).

If the elastic intrusions are distributed more or less uniformly throughout a volume of dimension large compared to that of each intrusion then throughout the resulting inhomogeneous medium the spatial variation of the functions L and M defined by (10) will be according to a more or less uniform periodic fluctuation about a constant value. It thus appears reasonable to approximate the fluctuation of L and M at any particular point by functions of the form

$$L(x_1, x_2, x_3) = A\cos(p_1x_1 + a_1)\cos(p_2x_2 + a_2)\cos(p_3x_3 + a_3) \quad (17a)$$

$$M(x_1, x_2, x_3) = B\cos(p_1x_1 + b_1)\cos(p_2x_2 + b_2)\cos(p_3x_3 + b_3) \quad (17b)$$

where A, B, a_i, b_i and p_i are constants. Substitution of (17a) and (17b) into (16) leads to

$$\tfrac{1}{2}(t_{11} - t_{33}) = \frac{wh}{8\pi(\lambda + 2\mu)^2}\{(p_3^2 - p_1^2)[\mu p^2 L - 2(\lambda + \mu)p_3^2M] + 2(\lambda + 2\mu)p_3^2p^2M\} \quad (18)$$

in which p^2 denotes $p_1^2 + p_2^2 + p_3^2$. Equation (18) shows that for fixed ratios of p_1, p_2, and p_3 the quantity $\frac{1}{2}(t_{11} - t_{33})$ is proportional to p^4. Hence the effect of uniformly distributed intrusions upon the shearing stress at any place is inversely proportional to the fourth power of the spacing between the intrusions. If the vertical and horizontal spacings of the intrusions are approximately equal then at sufficiently large depths the quantities p_1 and p_2 are approximately equal and a variation in the shear modulus μ affects the maximum shearing stress $\frac{1}{2}(t_{11} - t_{33})$ much more than does an equal variation in λ.

The above remarks and (18) concern the overall effect of many intrusions. To examine the effect of a single intrusion, (10) may be written in the form

$$hL = (x_3 + h)\int\!\!\int l\,dy - (\tfrac{1}{2})(\partial/\partial x_3)\int\!\!\int lr^2\,dy \quad (19)$$

the proof of which follows upon performing the differentiation with respect to x_3.

Consider first the additional stresses caused by a single spherical intrusion. Suppose that l and m have constant values l and m throughout a spherical region of radius c and let the coordinate origin of x_1, x_2, and x_3 be chosen at the centre of the sphere. Denote $x_1^2 + x_2^2 + x_3^2$ by R^2. Evaluation of the integrals in (19) is elementary and leads to the result that at any point (x_1, x_2, x_3) outside the sphere

$$\begin{aligned} hL &= lVR[h + (\tfrac{1}{2})(h - x_3)c^3/R^3 + (\tfrac{3}{20})x_3c^4/R^4] \\ &= hlV[R + (\tfrac{1}{10})c^3V^2R] \\ &\quad - (\tfrac{1}{2})lVc^3(\partial/\partial x_3)[R - (\tfrac{1}{14})c^2\nabla^2R] \end{aligned} \quad (20)$$

where V is the volume of the sphere.

Eq. (20) is exact and may be substituted into (16) to determine $\frac{1}{2}(t_{11} - t_{33})$ at any point external to the intrusion. The approximation $L = lVR$ is valid at large distances from the sphere and enables (16) to be written in the form

$$\tfrac{1}{2}(t_{11} - t_{33}) = -\frac{whV}{4\pi(\lambda + 2\mu)^2 R^3}\{3\mu l(x_1^2 - x_3^2)/R^2 + [2\mu + (9\lambda + 3\mu)x_3^2/R^2 - (\lambda + \mu) \cdot (3x_1^2/R^2 + 15x_3^4/R^4 - 15x_1^2x_3^2/R^4)]m\} \quad (21)$$

When $\sigma = \frac{1}{4}$ then λ and μ are equal to $(\frac{1}{3})E$ and hence a variation in E leads to equal values of l and m. Eq. (21) becomes

$$\tfrac{1}{2}(t_{11} - t_{33}) = \frac{-whV(m/\mu)}{18\pi R^3}\{1 - (\tfrac{3}{2})x_1^2/R^2 + (\tfrac{9}{2})x_3^2/R^2 - 15x_3^4/R^4 + 15x_1^2x_3^2/R^4)\} \quad (22)$$

whose dependence upon position in the material is as shown in Figure 1. If the intrusion has a higher modulus of elasticity E than the surrounding material, that is, if it is more rigid, then it is clear from Figure 1 that below the intrusion and within the cone bounded approximately by the surface $x_1 = 0.7x_3$ there is a region of increased shearing stress. However, outside this region the shearing stress is reduced. Conversely if the material is of lower modulus of elasticity E, that is, if it is of softer material, then the region of increased shearing stress is to the side of the intrusion outside the conical surface $x_1 = 0.7x_3$.

When $\sigma = \frac{1}{4}$ and $l = 0$ the equation (21) takes the form

$$\tfrac{1}{2}(t_{11} - t_{33}) = \frac{-whV(m/\mu)}{18\pi R^3}\{1 - 3x_1^2/R^2 + 6x_3^2/R^2 - 15x_3^4/R^4 + 15x_1^2x_3^2/R^4\} \quad (23)$$

which has values as indicated in Figure 2. Eq. (23) shows the effect of a variation of the shear modulus μ upon the shearing stress while (22) shows the effect of a variation in E. The effect of a variation in any two of the elastic constants may be obtained by the addition of suitable multiples of (22) and (23) and leads to a variation of shearing stress that is very similar to those of Figures 1 and 2.

At points just outside the spherical intrusion the approximation $L = lVR$ is no longer valid. However if the intrusion is at a depth h that is large compared to its radius then only the first two terms need be retained in (20). Since $\nabla^4 R = 0$ at all points outside the intrusion the second term in (20) contributes the following term to the right hand side of (16)

$$\frac{-whmV(\lambda + \mu)c^2}{40\pi(\lambda + 2\mu)^2}\left(\frac{\partial^2}{\partial x_3^2} - \frac{\partial^2}{\partial x_1^2}\right)\frac{\partial^2}{\partial x_3^2}\nabla^2 R$$

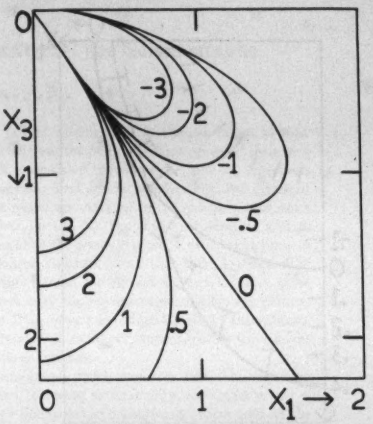

FIG. 1 – Increase of shear stress caused by an intrusion of increased elastic modulus E (Eq. 22); values of $[18\pi/(whVm/\mu)]\frac{1}{2}(t_{11} - t_{33})$ are indicated on each curve; x_1 and x_3 are the horizontal and vertical distances from the intrusion.

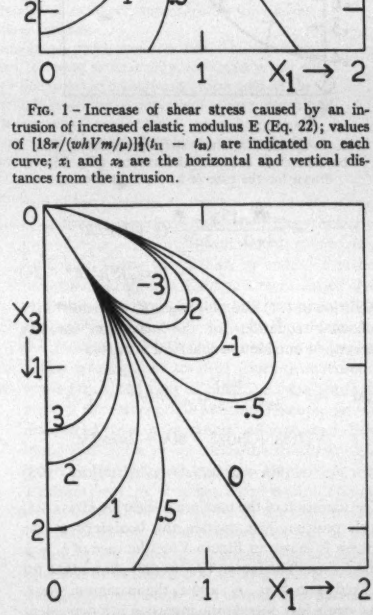

FIG. 2 – Increase of shear stress caused by an intrusion of increased shear modulus μ (Eq. 23); the units are as in Figure 1

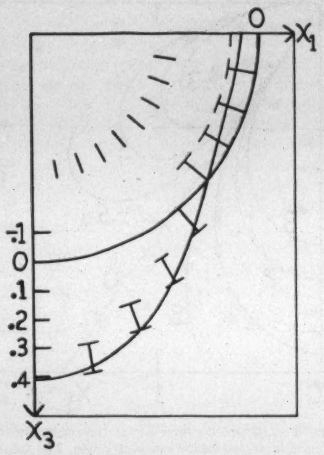

FIG. 3 – Increase of shear stress just outside (the boundary) of a spherical intrusion (Eq. 25) drawn for the case of $\lambda = \mu$ and $l = m$

$$= \frac{-whmV(\lambda+\mu)}{4\pi(\lambda+2\mu)^2}\left(\frac{8}{5}+3x_1^2/R^2 - 15x_3^2/R^2\right)c^2/R^5 \quad (24)$$

Addition of (21) and (24) when $R = c$ leads to the following equation for the maximum shearing stress just outside the spherical intrusion

$$\tfrac{1}{2}(t_{11}-t_{33}) = \frac{-whV}{4\pi(\lambda+2\mu)^2c^3}\{3\mu l(x_1^2-x_3^2)/c^2 + [2(3\lambda+8\mu)/5 - 6(\lambda+2\mu)x_3^2/c^2 - 15(\lambda+\mu)(x_3^4/c^4 - x_1^2x_3^2/c^4)]m\} \quad (25)$$

The variation of the maximum shearing stress (25) with position just outside the boundary of the sphere is shown in Figure 3 for the case of $\lambda = \mu$ and $l = m$. The factor V/c^3 in (25) shows that for a fixed ratio of x_1, x_2, and x_3 the maximum shearing stress just outside the intrusion is independent of the radius.

In general for a single intrusion of non-spherical boundary the expression corresponding to (20) requires an infinite number of terms. If the coordinate origin is chosen inside the intrusion the quantity r in (19) may be expanded in ascending powers of y_i/R. The first term in hL is $hlVR$ and so at a sufficiently large distance the effect of shape of the intrusion is unimportant. However, in order to determine the shearing stress at points close to the intrusion it is necessary to chose a simple approximation for each of the functions L and M in order to proceed directly from (16).

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Sensitivity Controls on Galitzin-Type Seismographs

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Abstract—In Galitzin-type seismographs a coil of wire is fixed to the pendulum so that when an earthquake forces the coil to oscillate between the poles of a strong magnet a current is generated. This current is passed through a sensitive galvanometer and its variations are registered photographically on the seismogram. Two special requirements for standard type of operation of these units are: (1) The resistance external to the galvanometer must always be such as to critically damp the galvanometer. (2) The combined effect of a magnetic damping device plus the resistance external to the pendulum coil must always be such as to critically damp the seismometer pendulum. Galitzin found that if he attempted to reduce the sensitivity of the system by diverting part of the current through a shunt, these special damping requirements could not be met until the maximum sensitivity was reduced to approximately 20 pct of the original value. The present investigation shows theoretically and experimentally how this range can be extended up to 70 pct, approximately, by a slight and sometimes negligible change in the pendulum damping.

In the experimental work a Sprengnether seismograph, which simulates the Galitzin in many respects, was used. The study was undertaken to record satisfactorily, through the use of sensitivity-control switches, the wide range of microseismic background experienced at the University of Washington Seismograph Station between the summer and winter months. The circuit and selector switch designs used to accomplish specified step reductions in sensitivity are described, and comments are made on certain operational problems concerned with optimum performance of Sprengnether seismographs.

In taking over the seismological work of the University of Washington late in 1953, the writer was faced with the problem of finding a simple and effective means of controlling the sensitivities of the Sprengnether seismographs in operation at the campus station. While it was immediately apparent that this equipment could occasionally be operated at maximum sensitivity during the microseismically quiet summer months, it was necessary during severe winter storms to reduce the sensitivity to as low as 10 to 15 pct of the maximum if serious overlapping of the seismogram traces was to be avoided. The desirable solution was to design a control box that would enable the operator to change the sensitivity by specified amounts through simply switching in new circuits.

In searching the literature for a quick solution, it was found that there was a surprising dearth of material on this particular phase of seismometry. It was ultimately learned that *Galitzin* [1914] had shown that in the so-called standard Galitzin hook-up it is not possible to obtain such reductions through circuit changes alone until the sensitivity is reduced to a very low fraction of the maximum—a fraction indicated by the ratio between the resistance of the galvanometer coil and its external critical damping resistance. As recent literature in English on the problem, including the resume of Galitzin's work by *Sohon* [1932] and other recent text books on seismology, provided no direct solution of the problem, the writer, not having a copy of Galitzin's work available, went ahead using as ground work the Galitzin equations as summarized by Sohon. It was found that, by making a rather minor modification of Galitzin's requirement that no change in damping adjustment was permissible, the sensitivity control could be increased from the 0–0.26 range to 0–0.70 if the constants of Sprengnether seismographs are used. Since the maximum sensitivity could also be obtained by a readjustment of the seismograph pendulum damping it was considered that a workable solution had been found and at the present time the University seismographs are being operated in conjunction with sensitivity-control switches based on the findings to be described in this paper. As the amplitude of the microseisms on the seismograms can be controlled by the switches the instruments are always operated at as high a sensitivity as the prevailing background will allow. This in itself is an outstanding practical advantage that overshadows any inconvenience resulting from a very infrequent damping adjustment that may or may not be required, or any misgivings that one may have concerning certain theoretical considerations which are currently under investigation.

Sensitivity control in Galitzin-type seismographs—In Galitzin-type seismographs the pendulum motion is recorded by mounting a coil of fine wire on the pendulum and having this coil oscillate (as

the result of ground vibration) between the poles of a powerful stationary magnet thus generating a current in the coil circuit. This current is passed through a photographically recording galvanometer. Since an infinite number of recording characteristics would be obtained if no restrictions were placed on the natural vibration period and damping of the pendulum and galvanometer Galitzin suggested certain procedures to standardize operational methods, reduce computational labor to a minimum, and produce calibration curves for different instruments that were reasonably comparable. He employed a pendulum mass so heavy that the galvanometer reaction on it was virtually negligible, stipulated that the galvanometer and pendulum periods should be identical, and that the galvanometer and seismometer pendulums be critically damped. (Sprengnether seismographs are generally adjusted to these conditions, but because of lighter-weight pendulums the galvanometer reaction does influence the pendulum motion so that the dynamic response characteristics are different.) In the Galitzin circuit the resistance external to the galvanometer must be held constant and equal to the CDRX (critical damping resistance) so that critical galvanometer damping will be maintained. The seismometer pendulum is magnetically damped by a copper plate (fixed to the end of the pendulum) between the poles of a strong magnet, but this is modified by the resistance in the circuit external to the seismometer. If this external resistance is changed, the magnetic damping must be changed to compensate for it. The sensitivity-control problem requires that these external resistances be maintained constant in so far as possible as shunt resistances are changed to reduce or increase the fractional part of the current which passes through the galvanometer. As previously indicated, it is found that the fractional part of the current passing through the galvanometer is subject to certain limitations which are brought out in the following analysis of the galvanometer-seismometer circuit.

The typical circuit for reducing sensitivity is shown on the left hand portion of Figure 1. The circuits will be developed for cases where the resistance of the seismometer coil is not equal to the critical damping resistance of the galvanometer.

Let R = resistance of seisometer coil and leads
ρ = resistance of galvanometer
Z = shunt resistance as shown in Fig. 1
X, Y = resistances as shown in Fig. 1
A = external critical damping resistance of galvanometer (CDRX)
B = resistance of circuit external to seismometer
m = fractional part of maximum sensitivity, the maximum being indicated by unity. In a circuit in which the seismometer pendulum remains critically damped m is ratio between current allowed to pass through galvanometer and maximum current generated when $m = 1$. The symbol $\overline{m}$ is same as m in a

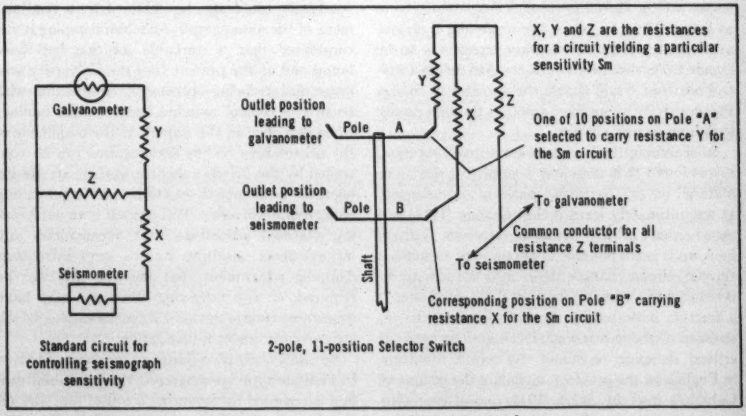

FIG. 1 – Typical circuit for reducing sensitivity

circuit in which B has been changed. For the general case m is ratio between (1) current passing through galvanometer in the changed circuit, and (2) current passing through when $m = 1$ in the unchanged circuit.

T_s = seismometer period

T_g = galvanometer period

From Figure 1 it can be shown that

$$A - Y = \frac{Z(X + R)}{Z + X + R} \tag{1}$$

$$B - X = \frac{Z(\rho + Y)}{Z + \rho + Y} \tag{2}$$

$$m(\rho + Y) = (1 - m)Z = B - X \tag{3}$$

Equations (1) and (2) are simply expressions of the rule governing resistances in divided circuits; (3) equates the drop in potential between two points on either side of the Z resistance, the total current generated being indicated by unity.

The following equations, derived from (1), (2), and (3) are used in computing X, Y, and Z for any value of m. If any computed resistance is negative, it means that the value m related to that particular circuit is not obtainable. Every computed resistance must be zero or positive if the corresponding m is to be real. The equations will aid in determining what that limit is.

$$X = \frac{m^2R(A + \rho) + B(B + R) - m(A + \rho)(B + R)}{(B + R) - m^2(A + \rho)} \tag{4}$$

$$Y = \frac{m^2\rho(A + \rho) + A(B + R) - m(A + \rho)(B + R)}{(B + R) - m^2(A + \rho)} \tag{5}$$

The computation will be much simplified if both numerator and denominator are divided by $(A + \rho)$. From (3)

$$X = B - m(\rho + Y) \tag{6}$$

$$Y = \frac{B - X}{m} - \rho \tag{7}$$

$$Z = \frac{B - X}{1 - m} \tag{8}$$

Since zero resistance must be associated with one of the obtainable values of m, both X and Y will be equated to zero to see what limiting value of m is obtainable in each case.

When $X = 0$

$$2m = \frac{B + R}{R} \pm \sqrt{\left(\frac{B + R}{R}\right)^2 - \frac{4B(B + R)}{R(A + \rho)}} \tag{9}$$

When $Y = 0$

$$2m = \frac{(B + R)}{\rho} \pm \sqrt{\left(\frac{B + R}{\rho}\right)^2 - \frac{4A(B + R)}{\rho(A + \rho)}} \tag{10}$$

In practice it was found (using Sprengnether constants) that over a wide range of m the values of X especially were negative and that m had to be reduced as low as 0.25 before X became zero. It was further found that the factor that caused this low value of m was the term under the radical in (9). It was decided to eliminate the radical by equating it to zero and learning what change in B was required to do this, even if this step involved a change in the damping adjustment of the seismometer pendulum. This new value of B, namely B_x, becomes

$$B_x = \frac{R(A + \rho)}{4R - (A + \rho)} \tag{11}$$

If under the same circumstances $Y = 0$ the expression under the radical becomes

$$B_x = \frac{4A\rho}{A + \rho} - R \tag{12}$$

Only one of these values of B_x will ever be used as illustrated in the sample computation to follow. Note that the subscript x has no relation to the circuit resistance X.

In the sample computation to follow it will be seen that with this new value of B_x workable values of m can be obtained that range from zero to 0.70. For the Sprengnether constants the problem of sensitivity control may thus be considered adequately solved. One may look upon this solution as one in which the maximum sensitivity of the network is reduced to 0.70 in order to obtain workable reductions in m without disturbing critical damping requirements; and one may add to this the maximum sensitivity obtainable ($m = 1$) provided the station operator is willing to readjust the pendulum damping for this special case in order to retain precise critical damping.

In cases where R (seismometer coil resistance) is greater than A (the CDRX) let G_0 be the original current passing through the galvanometer assuming that a shunt Z_0 has been placed across the circuit to get the proper external resistance for

critical galvanometer damping. B_0 will then be a new value for the resistance external to the seismometer. Then, assuming the emf equal to unity

$$G_0 = \frac{Z_0}{Z_0 + \rho}\left(\frac{1}{B_0 + R}\right) \tag{13}$$

The second term is the current generated in the whole circuit; the first term is the fractional part of it transmitted through the galvanometer.

Let G_y be the current passing through the galvanometer when the new resistance B_x is in the circuit,

$$G_y = \overline{m}\left(\frac{1}{B_x + R}\right) \tag{14}$$

where the last term is the current generated in the circuit, and $\overline{m}$ (a function of m) is an unknown reduction factor for this particular circuit, indicating the fractional part of the current passing through the galvanometer.

Since $G_y/G_0 = m$, the symbol $\overline{m}$ may be expressed in terms of the original m and the circuit constants

$$\overline{m} = \frac{mZ_0(B_x + R)}{(Z_0 + \rho)(B_0 + R)} \tag{15}$$

It should be clear that $\overline{m}$, not m, is the value to use for the m in (4)–(7) used in computing X, Y, and Z. One is faced with the choice of either calling m the actual reduction factor and using the value m (instead of m) in the equations; or calling $\overline{m}$ the desired fractional reduction and reserving the symbol m for the equations. The former usage is thought to be preferable.

TABLE 1 – *Computation of X, Y, Z*

Seismometer 388	$T_s = 1.35$ sec	$R = 2470$	
Galvanometer 19	$T_g = 1.35$ sec	$\rho = 600$	$A = 2220$

Z_0 and B_0 required for maximum sensitivity are

$$Z_0 = RA/(R - A) = (2470)(2220)/(2470 - 2220) = 21{,}940$$
$$B_0 = Z_0\rho/(Z_0 + \rho) = (21{,}940)(600)/(21940 + 600) = 584$$

These are simply computations of resistances in divided circuits.

Check m for negative resistances when $X = 0$

Eq. (9) $$2m = 3054/2470 \pm [(3054/2470)^2 - (4 \times 584/2820)(3054/2470)]^{1/2}$$
$$m = 0.974 \text{ or } 0.263$$

It is found from (4) that values of X for values of m lying between 0.974 and 0.263 are negative; the circuit is unsatisfactory. Now check m for negative resistance when $Y = 0$

Eq. (10) $$2m = 3054/600 \pm [(3054/600)^2 - (4 \times 2220/2820)(3054/600)]^{1/2}$$
$$m = 0.974 \text{ or a value greater than unity}$$

This circuit would be satisfactory for Y but not for X.

Making the term under the radical in (9) equal zero for reasons previously explained

Eq. (11) $$B_x = (2470 \times 2820)/[(4 \times 2470) - 2820] = 986$$

This is new value of B required to yield all positive values of X.

The corresponding value of m, using the new value B_x, will be

Eq. (9) $$2m_x = 3456/2470 = 1.399 \qquad m_x = 0.700$$

This is maximum value of m obtainable with 'B_x damping.'

It is desired to compute circuits for $m = 0.50, 0.25, 0.125$, and 0.0625 using the new value B_x

Eq. (15) $$\overline{m} = 21{,}940(986 + 2470)m/[(21{,}940 + 600)(584 + 2470)] = 1.101m$$

Eq. (4) $$X = (2470\,\overline{m}^2 + 1209 - 3456\overline{m})/(1.226 - \overline{m}^2)$$

The numerator and denominator of (4) have been divided by $(A + \rho)$

$\overline{m}$	$\overline{m}$	$\overline{m}^2$	$-3456\,\overline{m}$	$2470\,\overline{m}^2$	Numerator	Denominator	X	Y[b]	Z[b]
1.00[a]	...	...	...	...	...	...	0	0	21940
0.50	0.551	0.3037	−1909	750	50	0.922	54	1090	2078
0.25	0.275	0.0759	−954	187	442	1.150	384	1586	830
0.125	0.138	0.0190	−477	47	779	1.207	645	1870	396
0.0625	0.0689	0.00475	−238	12	983	1.221	804	2042	195

[a] The resistance external to the seismometer is B_0 for $m = 1$ and B_x for all other values. When shifting from one to the other an adjustment of magnetic damping is theoretically required.

[b] Y and Z are computed from (7) and (8), using $\overline{m}$, not m.

In cases where R (seismometer coil resistance) is less than A (the CDRX), the shunt is not needed to obtain maximum sensitivity, but a resistance X_1 needs to be added to the circuit resistance in order to obtain the required value of A. In this case the original current passing through the galvanometer will be

$$G_0 = \frac{1}{B_0 + R} \tag{16}$$

where B_0 is equal to $\rho + X_1$. Since $Z_0/(Z_0 + \rho)$ in (13) and (15) is now equal to unity (15), when used for the case where R is less than A, becomes

$$\overline{m} = \frac{m(B_x + R)}{(B_0 + R)} \tag{17}$$

In computing circuits it is first desirable to learn what maximum value of m other than unity is obtainable. Equations (9)–(12) serve this purpose. One may or may not use it in the control switch, just as he chooses. All lower values are obtainable. The writer uses this last circuit as a basis for computing all values of m except the special case in which m is unity and the sensitivity is the maximum obtainable. In making the computations, it is desirable to use four-place logarithms and list on a scratch pad the values of the 10 or 12 terms used in the equations together with their logarithms.

Since the discussion up to this point deals basically with the theory of circuits intended to reduce the sensitivity of Galitzin-type seismographs, it should be made clear that the writer has had no Galitzin-type seismograph on which to check the possibilities of sensitivity control by the method just outlined. In the sample computation, Table 1, Galitzin seismograph constants are not used so that it represents only a hypothetical case insofar as the Galitzin is concerned. It is felt, however, that the computation will serve as a useful guide to anyone who desires to investigate sensitivity controls on Galitzin equipment using actual Galitzin constants and at the same time show the actual figures obtained when the equations are applied to the constants of a Sprengnether seismograph. Resistances are expressed in ohms.

Damping tests were made on the above instrument with both B_0 and B_x in the circuit. It was found that if the damping were critically adjusted to the B_0 resistance, and then the B_x were used without further damping adjustment, the B_x damping would be 0.97 critical instead of critical. For most operational purposes this difference is negligible so that with the B_0 resistance in the

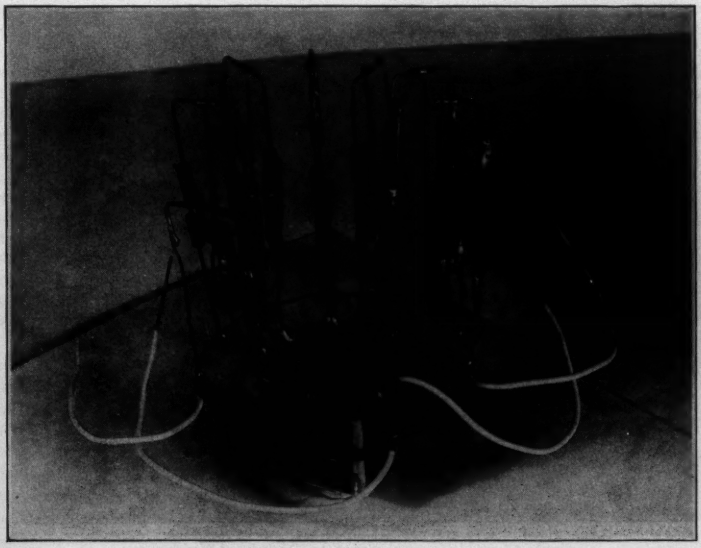

FIG. 2 – Two-pole, eleven-position rotary selector switch

circuit satisfactory performance could be expected for all sensitivity settings.

Application of sensitivity control equations to Sprengnether seismographs—The foregoing equations were developed primarily to compute circuits that would provide sensitivity controls on the Sprengnether seismographs. Sensitivity observations on the seismographs when various reduction circuits were introduced checked, within the limits of observational error, the reduction for which each circuit was designed. Casual inspection of background recordings made at various sensitivity settings of the control box also indicated that the intended amplitude reductions were being realized. Since the sensitivity tests involved only the measurement of the angular displacement of the galvanometer suspension when the seismometer boom was manually displaced through a known angle the dynamic characteristics of the lighter weight Sprengnether pendulum did not come into the picture. While as previously stated, the calibration curve of the Sprengnether may be different from that of a Galitzin having similar constants, it appears that this difference does not play a vital role in relative sensitivity tests of the kind here outlined. The primary objective was attained, namely, the control of trace amplitudes through instant switching in of new circuits without change of damping characteristics other than in the special case named; and this can be taken care of with little additional labor whenever operation at maximum sensitivity becomes desirable. At Seattle this occurs very seldom in the course of a year. Recent investigations of the Sprengnether seismograph by *Eaton* and *Byerly* [in press; Eaton, in press] should furnish new and important information on the operational characteristics of Galitzin and Sprengnether seismographs. It is presumed that the report of these investigations will clarify the relationship between sensitivity tests and response curves in a manner that will provide a further evaluation of the sensitivity control circuits described in this paper.

The remaining paragraphs will be devoted to a description of the mechanical features of the control box designed to house the various circuits and to a number of things that were found to influence the sensitivity of Sprengnether seismographs aside from circuit design.

A two-pole, eleven-position, rotary selector switch on which seven different circuits are mounted is shown in Figure 2. In the picture the three resistances in each circuit are visible although

FIG. 3 – View of seismograph pier at the University of Washington

in some cases it is apparent that two resistor units are needed to obtain the desired values of X, Y, and Z. The two leads on the viewer's right go to the galvanometer outlets of the control box; those on the left go to the seismometer outlets. Figure 1 shows the theoretical circuit and also shows how each circuit is built up on the selector switch. To test the circuits, one can first connect an ohmmeter to the galvanometer terminals of the control box and see that the resistance external to the galvanometer is equal to the CDRX in all positions of the selector switch, being sure, however, to place a resistance across the seismometer outlets that is equal to the resistance of the seismometer coil. In like manner, the ohmmeter can be connected to the seismometer outlets, and with a resistance equal to the galvanometer resistance placed across the galvanometer outlets, check the resistances external to the seismometer. At all selector switch settings except the maximum ($m = 1$) the resistance should be B_x. For the maximum it should be B_0.

Figure 3 is a view of the seismograph pier at the University of Washington. The four sensitivity-control boxes are seen between the recorders and the galvanometers. A flick of a switch changes the sensitivity on any seismograph unit. Each of the two recorders in the background registers two horizontal components—long and short period units—for a 24-hour period. It was on these seismographs that sensitivity tests were made at the different sensitivity settings to verify the equations. In each case the seismometer coil resistance was higher than the CDRX of the galvanometer and shunts had to be used to obtain critical galvanometer damping. Readers may be interested in a note by *Neumann* [1954] describing the method used to obtain individual critical damping of Sprengnether pendulums and the Leeds and Northrup galvanometers used with them. It was found that the amplitude of pendulum displacements during damping tests must be kept small otherwise serious error is introduced.

It was noted during the investigation that the position of the pendulum coil with respsect to the poles of the coil magnet exerts a great influence on sensitivity. If a constant sensitivity is to be maintained, the coil must not be allowed to drift from some selected operating position. Ordinarily the front face of the magnet on a Sprengnether short-period instrument is 30 mm from the far side of the coil box fixed to the seismometer boom. In a sensitivity test made in this position, a light-spot deflection of 100 mm was obtained when, following the Galitzin method described by *Sohon* [1932, p. 123], the pendulum was given a quick displacement of 0.001 inch at a distance of 15 cm from the hinges. When the magnet was moved away from the coil in four steps of 5 mm each, the successive deflections were 115, 127, 140, and 130 mm. Compared with the deflection of 100 mm obtained with the magnet in operating position the figures show the relative increases in sensitivity obtained in the various positions. The maximum of slightly over 140 mm occurred when the magnet was set back 16 mm and the face of the magnet was aligned with the inside edge of the coil box. When the magnet was moved closer in on the coil box in two steps of 5 mm each, the deflections dropped to 75 mm and 22 mm. These figures define fairly well a graph made from 33 position tests. While this is a disadvantage in most respects, it provides a means of equalizing the sensitivities of a pair of horizontal component units if one is willing to modify slightly the method used by the manufacturer to hold the coil magnets in a fixed position.

One other feature of the short-period Sprengnether should be called to the attention of the station director who aims at precision adjustments. If the pendulum is removed and suspended as a simple gravity pendulum, it will be found that the center of gravity is 3.5° off the center line of the pendulum boom because of the off-center position of the damping vane. This should be taken into account in orienting the seismometers on the pier.

In conclusion the writer feels that, insofar as the controls on Sprengnether seismographs are concerned, they eventually can be well adapted to quantitative measurement if the suggested precautions are taken including critical damping of the seismometer pendulum. In the only local earthquake where the iP impulse was large enough to be measured, the University of Washington's short-period seismographs gave, with reasonable accuracy, a correct azimuth on an epicenter that was well determined from both field and instrumental data.

Where quantitative measurements are contemplated, existing uncertainties concerning the degree to which the Sprengnether may or may not duplicate the performance characteristics of a bona fide Galitzin seismograph should be clarified by the previously mentioned investigations of Byerly and Eaton.

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Report of the Special Committee on Cosmic-Terrestrial Relationships for the Year Ending June 30, 1956

HARLAN T. STETSON, *Chairman*

ROSS GUNN, SERGE A. KORFF, ROBERT A. MCMATH, DONALD H. MENZEL, HERBERT RIEHL, W. H. THOM, JR.

A noted change in solar activity has taken place during 1955–6. Sunspot activity as marked by the Zurich monthly numbers has increased from a low of 0.2 in June 1954 to a sunspot number of 122.6 in February 1956. The rise has been precipitous during the twelve-month interval from March 1955, from a value of 4.7 to values exceeding 120. This increase in activity has afforded opportunity for a study of correlations of solar disturbances with disturbances in the ionosphere and geomagnetic variations.

In the Committee's report for last year [*Trans.*, pp. 1061–1066, Dec. 1955] a suggestion was made to observatories providing sunspot counts, that separate sunspot numbers be issued for the old and new cycle spots during the interval of overlap. Menzel, of our committee, presented this recommendation at the meeting of the International Astronomical Union (IAU) in Dublin last summer. The suggestion met with some favorable response, but it was pointed out by Waldmeier of Zurich that he personally felt any new techniques, which would necessarily enter into the Zurich number, would perhaps disturb the old standards on which the Zurich numbers have been based. No action on the part of the IAU has yet been reported. Since we are now well past the 1954 minimum of sunspots, the question does not become a serious issue for the current cycle.

Solar research has been augmented at the Harvard Observatory through the informal organization mentioned last year as the 'Solar Associates,' and also by change in location of the Astrophysical Observatory of the Smithsonian Institution from Washington to the Harvard Observatory at Cambridge.

Donald H. Menzel, Director of the Harvard Observatory, reports for the year as follows:

The development of instrumentation for the Air Force Sacramento Peak Observatory, Sunspot, New Mexico, has continued. The large 16-inch coronagraph has given excellent records of both prominences and the solar chromosphere, in the hands of Richard Dunn and Frank Q. Orrall. These motion pictures are expected to throw great light on the nature of activity in the solar atmosphere. The survey records include studies of the disk, prominences, and coronal spectra. Dunn has recently been successful in obtaining direct photographs of the solar corona in the light of 5303, the green coronal line. John W. Evans, Henry J. Smith, and Elske P. Smith have completed installation of the large spectrograph, which operates at the Coude focus of the large coronagraph.

At Cambridge, Max Krook, David Layzer, and D. H. Menzel have continued new studies of the dynamics of ionized gases, including the phenomenon of turbulence. The study of the E layer, undertaken by Menzel and John G. Wolbach, referred to in the report for last year, is complete. The papers, now in press, include a detailed theory for the E layer, in an atmosphere possessing a constant temperature gradient. The analysis leads to a prediction of the E-layer critical frequencies as a function of latitude, day of the year, time of day, and phase of the sunspot cycle. The analysis was carried for three separate latitude coordinates, namely, geographic, geomagnetic, and magnetic dip. Apparently the last gives the best fit. The analysis for the F2 layer is continuing but progress is slow because of the complexity of the problem.

Activities at the McMath-Hulbert Observatory of the University of Michigan, of which Robert A. McMath is Director, has been reported by Helen W. Dodson as follows:

During the year 1955–1956, the McMath-Hulbert Observatory has continued its program of basic solar research. The high-dispersion vacuum spectrograph, the Stone spectrograph with a new Babcock grating, and the spectroheliograph of the 50-foot solar tower were all used for observations that had some bearing on problems relating to solar-terrestrial relationships.

Flare spectra have been obtained with both spectrographs. High dispersion spectra centered on Hα, the K line, and on chosen portions of the ultraviolet region, have been taken with the vacuum spectrograph at the time of certain flares. The Stone spectrograph has been used to record the Hα line at short time intervals throughout the development of flares. Spectroheliograms made at the same time with the tower telescope have provided general records of changes in either Hα or K_{2v}, while ionospheric records monitored simultaneous ultraviolet radiation from the flare.

A photometric study of 194 solar flareas has indicated that except in unusual cases a maximum Hα intensity of the order of 0.8 of the local continuum is both necessary and sufficient for the occurrence of a simultaneous ionospheric disturbance that satisfies current standards of certainty and generality. Ionospheric disturbances are seldom reported unless the area of the flare is of the order of 200 millionths of the solar disk. In general, the larger and brighter the flare,

as seen from the Earth, the greater the associated ionospheric disturbance. However, certain relatively small, faint Hα flares near the solar limb have caused disproportionately large ionospheric disturbances. This suggests that there is apparently less diminution from center to limb for the ionizing radiation from flares than for Hα. Near the limb, the ionospheric disturbance often lasts longer than the Hα flare.

A comparative study has been made of the resumption of solar activity and geomagnetic storms after the 1954 minimum in the solar cycle. The four months May–August 1954 marked the minimum in the cycle of geomagnetic disturbances. Three magnetic storms occurred in September. Solar activity, including flares, outbursts, and enhanced coronal and radio-frequency emission, took place in August, especially between August 20 and 27. During September, solar activity was again very low. It is possible that the September 1954 magnetic storms reflect only the well known increases in geomagnetic disturbances in March and September. On the other hand, any attempt to explain them in terms of preceding solar activity involves time relationships far different from those generally considered acceptable in such matters.

E. O. Hulburt retired from active duty from the Naval Research Laboratory as of January 1, 1956. Because of retirement, Hulburt wished to be relieved of duties on the Special Committee on Cosmic Terrestrial Relationships on which he was most helpful as Vice-Chairman for the last six years. The program of the Naval Research Laboratory (NRL) embraces a variety of topics in the field of cosmic terrestrial relations concerning which John A. Sanderson, Chief of the Optics Division, has been so kind as to prepare the following summary for our Committee.

Radio astronomy—The radio emission from the Sun at wavelength 9.4 cm was measured at Oskarsham, Sweden, during the total solar eclipse of June 30, 1954. The data have been corrected for instrumental and background radiation changes occurring during the eclipse, and a radial brightness distribution has been calculated under the assumption of spherical symmetry. This brightness distribution has the limb-brightened form predicted by quiet sun theory under the same assumption of symmetry. Maximum limb brightness was about twice the value for the center of the Sun. The eclipse curve corresponding to the calculated brightness distribution agrees with the measured eclipse curve within one per cent. A redistribution of a small fraction of the total 9.4 cm radiation to the equatorial limb regions of the calculated distribution improved the agreement with the measured eclipse curve slightly.

The distances to three so-called radio stars have been determined by a new method employing the radiation and absorption by galactic hydrogen at wave-length 21 cm [*Hagen, Lilley,* and *McClain,* 1955; *McClain,* 1955].

Also by means of this radiation, a determination of the red shift, ascribed to expansion of the universe, has been made for a pair of colliding galaxies in Cygnus, and a velocity of recession of about 17,000 km/sec has been determined, in agreement with the value from optical measurement. Since the frequency of 21 cm radiation is remote from optical frequencies and the indicated velocity is the same for both, this measurement offers another confirmation of the expansion theory but does not rule out other possibilities [*Lilley* and *McClain,* 1956].

It has been found that the spectra of all well-observed nonthermal radio sources can be explained on the basis of the same underlying source spectrum of the form $I(\nu) \sim \nu^{-\alpha}$, where I is the spectral intensity at frequency ν and α is a constant. This is the form expected for synchrotron radiation and by absorption in ionized gases in front of the source. The latter are in two forms: interstellar gas, known from optical data to be approximately uniformly distributed near the galactic plane, and extremely dense gas covering most but not all of each source. The varying extent to which the dense gas covers each source explains observed spectral differences.

The attenuation of 8.6 mm radiation by clouds was investigated by observations of the Sun through clouds. The attenuation by thin cirrus clouds was less than 0.1 db and by low dense cumulus clouds, 2 db. There was a good correlation between optical and 8.6 mm transmission by low dense clouds.

Upper atmosphere—A theoretical investigation of ionospheric propagation was conducted to correlate NRL rocket measurements with ground observations. This has provided: (a) a verification of electron densities measured during flights of V-2 no. 49, Viking 5, and Viking 10; (b) a new method for deducing electron densities from virtual height ($P' - f$) recordings; (c) a complete set of reference curves for performing the analysis with records taken at White Sands; (d) a number of computed electron density profiles, all of which show the peak of the F2 region to occur near 300 km at White Sands Proving Ground, New Mexico [*Jackson,* 1956].

A study of previous rocket data indicates that the D region begins at about 75 km under quiet conditions but that the absorption of radio waves of a few megacycles per second is not strong below 90 km. Maximum absorption occurs in the lower edge of the E region where the electron density is approximately 10^5 per cc.

During 1955 three Aerobee rockets equipped with Bennett radio-frequency mass spectrometers were flown to investigate the composition of the upper atmosphere. Two rockets carried identical dual ion spectrometers to determine simultaneously the positive and negative ion composition of the lower E region. The spectrometers function above 93 km where the mean free path is long enough to permit resolution.

The first experiment was performed at night. Only positive ions at mass 28 appeared, between 93 km and the peak of the flight at 115 km. The position of the mass 28 peak on the record agreed with laboratory calibration within ± 0.5 mass unit. Positive ions other than mass 28 would have been detected if present in concentration one per cent of the observed mass 28 concentration. Mass 28 is attributed here to N_2^+; the possibility that it could be CO^+ seems remote in consideration of the relative abundances of the unionized molecules. Negative ions were not detected, although concentrations of one per cent of the observed N_2^+ concentration should have been detectable.

The second rocket was flown in daylight. Negative

ions appeared at mass numbers 46, 32, 29, 22, and 16, between 93 km and the peak of the flight at 131 km. Mass 46 was predominant, the relative abundances being 96.5, 1.6, 0.2, 1.0, and 0.7 in order of decreasing mass. There was no indication of positive ions during this flight.

The third rocket was equipped to determine the gas composition of the upper atmosphere. Atomic masses 46 and 23, in addition to normal atmospheric constituents, were detected in the 74-km region.

Arctic upper-atmosphere pressure data obtained from four balloon-launched rockets during the summers of 1953 and 1954 were reduced. The atmospheric density profile in the 25- to 45-km region was found, within the experimental error, to be the same as the Rocket Panel, White Sands values. The measured atmospheric pressure and the computed temperature for the flights at 62°N and 74°N were found to be as much as 30 pct higher than the White Sands values in the 30- to 45-km region, but approximately equal to the latter values at 70 km. At 74°N, a high lapse rate was indicated within the region 44- to 60-km [*LaGow* and *Ainsworth*, 1956].

The effect of thermal conductivity on controlling the temperature distribution of the high atmosphere was calulated. The results indicate that the atmosphere is isothermal above 250 km, and that between 100 and 200 km there is a strong positive temperature gradient. The temperature in the isothermal region was assumed to be 1100°K, in order to provide enough atmosphere near 300 km to support an F2 region. The low temperature at 80 km is caused by lack of energy absorption rather than by the presence of a strongly emitting layer [*Johnson*, 1956].

The night airglow was investigated with photometers of 20 A spectral band pass which were flown in a rocket on December 12, 1955 to determine the distribution in altitude of the emission in the 5577 A oxygen line, the sodium D lines, and the background at 5300 A. The results showed that the luminosity from the 5577 A line lies between 80 and 115 km with maximum intensity at 97 km, and from the D lines, between 70 and 100 km with maximum at 85 km. A large portion of the 5300 A luminosity originated in approximately the same region as the oxygen green line. Preliminary data for the 5577 A line from a similar experiment flown a few days earlier are in agreement.

Two balloon-launched Deacon rockets equipped with appropriate counters were flown in the northern auroral zone in further investigation of high radiation intensities previously observed by *Meredith* and others [1955]. The instruments operated well, and the data are being analyzed.

The theory of magnetic self-focusing streams has been further developed and applied to streams of protons projected from the Sun [*Bennett*, 1955].

The Störmertron tube, which produces accurately to scale the orbits of charged particles in magnetic fields, has been further developed for studying more accurately the orbits of charged particles in the Earth's magnetic field, including the paths of charged particles shot out of the Sun. Numerous features of aurorae and associated magnetic disturbances have been accounted for by the solar proton stream theory and the stream forms shown to exist using the Störmertron.

Micro-meteors were detected through craters produced by particle impacts on a moving film detector in an Aerobee rocket. Analysis of the data is proceeding.

Cosmic rays—Data from balloon flights showed that the primary cosmic ray proton and alpha particle intensities at latitude 55°N were 0.19 and 0.032 cm^{-2} $steradian^{-1}$ sec^{-1}, respectively. The alpha particle mean free path in air was found to be 35 ± 7 gm cm^{-2} [*Davis*, *Caulk*, and *Johnson*, 1956].

In a 29-km balloon flight near the geomagnetic equator, an unusual high-energy phenomenon has been observed in a stack of stripped emulsions. A 20-Bev electromagnetic cascade develops from an electron pair whose origin cannot be spatially resolved from the track of an extremely energetic, $(1.7 \pm 0.5) \times 10^{14}$ ev helium nucleus. Various explanations of this event have been explored, of which none yields a probability higher than 5×10^{-5} that it should have been observed under the conditions of exposure. This probability is that for Bremsstrahlung [*Seeman* and *Glasser*, 1956].

The assumption of charge conjugation invariance, as used by Gell-Mann and Pais to discuss the decay of the θ^0 meson into two π mesons, has been applied to the decay of the τ^0 meson into three π mesons. Analogous to the θ^0 meson case, the τ^0 meson is considered as a 'particle mixture' exhibiting two distinct life times.

A critical evaluation of the basic properties of mesons and hyperons has been made, and a table prepared [*Shapiro*, 1956].

A Monte Carlo analysis of the nuclear production of Λ^0 and θ^0 particles has been carried out [*Block* and *Jastrow*, 1955].

Solar radiation—Three rocket flights in October–November 1955 revealed that the general level of Lyman alpha (1216 A) intensity was about five ergs/cm^2/sec at the top of the Earth's atmosphere. These were the most recent observations in a series which began in 1949. The lowest intensities observed were about 0.1 erg cm^{-2} sec^{-1} in 1952, so that the current results represent an enhancement of about 50 times the minimum intensity. No visible flare or SID coincided with any of the rocket experiments [*Byram*, *Chubb*, *Friedman*, and *Kupperian*, 1956].

Solar x-ray intensities during the same flights followed closely the visible activity of the corona and the normal trend of E-region ionization as the maximum of the sunspot cycle is approached.

Audio-frequency atmospherics—Spectrographic analysis of the simultaneous recordings of whistlers made at Dartmouth College and the Naval Research Laboratory showed excellent agreement in their activity and character at the two locations. Analysis of simultaneous observations in Alaska and New Zealand, at magnetically conjugate points, showed agreement with Storey's theory [*Morgan* and *Dinger*; 1956, *Storey*, 1953]. However, it appears that modifications of present theory will be required to explain anomolous types of whistlers associated with intervals of high magnetic activity [*Dinger*, 1955a].

Diurnal variations of whistlers and 'dawn chorus' and their correlation with other geophysical phenomena are being studied [*Dinger*, 1955b].

From the point of view of problems of the Earth's crust and extraterrestrial phenomena, W. H. Thom reports that the tectonic compilation work that he has been carrying forward suggests

that some of the dominant fracture-systems characterizing the Earth's crust have resulted from the impact effects of very large meteorites. He concludes also that repeated lateral shiftings of large crustal segments apparently have resulted from the combined effect of regional changes in elevation, plus the rotational movement of the globe.

S. A. Korff of New York University, who is Executive Secretary, Cosmic Ray Technical Panel of the United States National Committee for the International Geophysical Year, reports on the activities of his group during the current year as follows:

We have continued our long-term program studying cosmic-ray neutrons. Last summer we completed the last of our current series of balloon flights, and have prepared a semifinal report. In this report we have reviewed the work done by our project, and likewise presented some new balloon measurements. The net result of this work is a consistent picture of neutron production throughout the atmosphere, at various latitudes from the pole to the equator. This report formed the Doctor's thesis of Robert Soberman and was also presented at the Mexico meetings of the American Physical Society and the Cosmic Ray Conference.

We have also completed a study of the energy distribution of the neutrons in the atmosphere. This study was necessitated in order to enable a comparison to be made of neutrons as measured by ourselves and by other observers. This energy-distribution study required additional flights in airplanes with various types of neutron counters. The report on this is at present being written up, and is planned to constitute the doctoral dissertation of John Gabbe. This report will enable comparisons to be made between our work and that of other people, and will show that corrections are required in order to allow comparisons of neutron-counting rates in counters which were inside pyrex envelopes and ones which were in brass envelopes. The cadmium shielding was also measured.

We have started construction on cosmic-ray equipment to be used during the International Geophysical Year. This will include the operation of a neutron monitor of the Simpson standard type at a far northern latitude. It is hoped to install this meter during the coming summer.

Another set of calculations has been made in the domain of magnetohydrodynamics about the effects of the cosmic-ray particles in the field produced by charged particles moving outward from the solar system. This analysis will materially help us to understand some of the calculations in the radiation and other counters with solar and terrestrial phenomena. This report will be the doctoral dissertation of Arthur Beiser, and is expected to be ready shortly.

A further analysis of the isotopes produced in the surface of the Earth and in the oceans and atmospheres was made by me. This paper was presented to the New York Academy of Science and was awarded the Pregel Prize. It is now being prepared for publication. In the paper, a large number of reactions are examined and it is shown that most of them do not produce observable quantities of new isotopes. However, several promising lines of future investigation are indicated. The conditions involved in long-time equilibrium are considered and the rate of production of a number of stable isotopes are examined. It is found, for example, that such isotopes as oxygen 17 and nitrogen 15 in the Earth's atmosphere cannot be attributed to cosmic radiation nor can the deuterium content of the ocean.

Although in previous years various meteorological investigations have suggested relationships between solar activity and meteorological changes, Herbert Reihl, in covering this field, states:

Very little has been published on solar-weather relations during the past year in scientific journals. Almost the only exception is an article by *Farthing* [1955]. Nevertheless, much research activity has taken place; this has encouraged the High Altitude Observatory at Boulder, Colorado, to sponsor a six weeks' summer seminar in 1956 on solar-weather relations, to be followed by a meeting of the American Meteorological Society at Boulder on the same subject.

The writer has studied circulation changes at 500 mb in the belt of aurora in an attempt to arrive at possible physical relations between tropospheric circulation changes and solar activity. It is shown that, as far as can be determined, a 'direct' meridional circulation cell does not develop at 500 mb following solar outbursts. Changes of the circulation in the auroral belt are produced by mechanical momentum export or import through the boundaries of the belt. The momentum convergence, oddly, has a period corresponding to the mean equatorial rotation of the Sun.

Definite conclusions cannot be drawn from the short period investigated. The method however appears sufficiently promising to recommend extension of the approach developed.

Edward M. Brooks of St. Louis University briefly summarizes *Some weather-sunspot correlations* as follows:

Data for the interval 1916–50 indicate that the monthly relative sunspot number had mostly negative correlations with St. Louis monthly mean temperature (−0.35 in June) and mostly positive correlations with St. Louis monthly precipitation (+0.45 in January). The temperature and precipitation were negatively correlated with each other in the warmer half of the year (−0.51 in May) and positively correlated in the colder half (+0.44 in March).

The monthly number of days on which tornadoes were reported in the United States showed consistent positive correlations throughout the year with both St. Louis temperature (+0.49 in January, but June negative) and St. Louis precipitation (+0.68 in March), the precipitation correlations being the highest of all the correlations computed.

Sunspot number and the number of tornado days in the United States had no significant correlations, but a map showing the correlations between sunspot number and the number of days with tornadoes in each of the states has areas of positive correlation extending from Oklahoma to Pennsylvania (+0.56)

and in Florida (+0.66), and negative correlation from South Dakota to Michigan (Wisconsin, −0.35).

Sigmund Fritz of the U. S. Weather Bureau states:

During the past year the Weather Bureau has analyzed sky-brightness data obtained from photometers at Climax, Colorado, and Sacramento Peak, New Mexico. These data have been related to changes in the turbidity of the atmosphere and to variations in the amount of solar radiation reaching the ground on clear days as determined by pyrheliometric measurements from a number of stations. In particular the turbidity introduced by a volcanic explosion in Alaska in 1953 as measured by pyrheliometers has been investigated [*Fritz*, in press]. The Smithsonian solar constant readings for the past 30 years have been analyzed statistically to determine whether any significant relationship exists between measurements made at widely separated stations. Further studies have been conducted to determine whether relationships can be established between various solar indices and changes in the weather and circulation patterns. Sunspot and corona data are obtained on a current basis and examined for any clues that might lead to the understanding of any unexplained weather changes. Studies on the prediction of sunspot activity have been made and are continuing.

The relation between solar energy and the lower atmosphere continues to be examined. Since no physical explanation for possible solar weather relations has been generally accepted, the data and estimates for enhanced emission from the sun have been summarized. Most estimates show the enhanced energy to be a very small fraction of the solar constant, and that this energy is absorbed in the upper atmosphere by less than 10^{-4} of the atmospheric mass. Although no rigorous proof is now possible, most meteorologists would consider that this direct heating effect is not important.

Indirect effects such as the formation of condensation nuclei, with a subsequent increase in cloudiness, offer a possible explanation. But Dubois has recently found that the albedo of the Atlantic sector of the Earth increases during sunspot minimum. Thus the physical connection between enhanced emission from the disturbed Sun and possible weather changes remains uncertain.

The transmission of solar energy through overcast clouds has been computed as a function of the albedo of the underlying surface among other parameters [*Fritz*, 1955]. The solar energy measured on the Arctic Ice Island T-3 is being investigated, and the transmission through clouds is being studied in relation to the theoretical computations.

Important material in the field of cosmic-terrestrial relationships is to be found in the Director's reports of the Department of Terrestrial Magnetism of Carnegie Institution of Washington and in the various research papers and reports issued by the Central Radio Propagation Laboratory of the National Bureau of Standards now located at Boulder, Colorado. Of particular interest to investigators in the field of cosmic terrestrial relationships are the CRPL monthly publications *Ionospheric Data* and *Solar-Geophysical Data*.

Attention should be called to the second volume in the *Solar System Series* edited by Gerard P. Kuiper, entitled *The Earth As A Planet* which has recently been published by the University of Chicago Press. The table of contents suggests a wealth of information as to the relation of the planet Earth to its cosmic environment.

In closing this report the Chairman wishes to express appreciation to the Superintendent of the U. S. Naval Observatory for the promptness with which its Solar Division has issued daily sunspot data. The Chairman would also express his appreciation to the various members of the Committee for their interest and prompt collaboration in preparing these reports during the three-year period for which the Committee received its appointment.

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Discussion of "The Displacement of Calibration Curves for Electrical Soil-Moisture Units"

BY IRWIN REMSON AND G. S. FOX

[*Trans.*, **36**, 821–826, 1955]

F. R. Dreibelbis (Soil and Water Conservation Research Station, U. S. Department of Agriculture, Coshocton, Ohio)—This paper seems to leave unanswered a number of questions pertaining to the calibration of soil-moisture units. In Remson and Fox's discussion of results they list five facts that are shown by the calibration.

The first three deal with the second drying curve being different than the first, and subsequent dryings being similar to the second one. Similar findings were brought out before by *Bouyoucos* [1949], and later substantiated by *Colman* [1949] and by others including the work at the Coshocton Station. The writer's discussion, however, is confined to the discrepancy of field calibration with laboratory calibrations which comprise the fourth and fifth facts discussed by Remson and Fox.

The writer does not agree with their conclusions concerning "the general unreliability of laboratory calibrations of soil-moisture resistance blocks." In working with the Coshocton fiberglas gypsum blocks [*Youker* and *Dreibelbis*, 1951], reasonably good agreement has been obtained when laboratory calibrations were compared with field sampling on the Keene silt loam (see Fig. 2) and on the Muskingum silt loam. The authors' conclusion undoubtedly applies to their technique of laboratory calibration with Sassafras loamy sand. Their conclusion that it applies to all soil-moisture resistance blocks appears unjustified. Since their results seem to be at variance with investigators who have long been studying soil moisture, such as Bouyoucos, Colman, and others, it would be helpful to know some of the details of their technique.

It is suggested they state: (1) whether temperature corrections were made in their field readings; (2) what method of sampling was used to obtain their samples in sand (moisture of 35–37 pct by volume seems quite high for sand); (3) whether soil cores were dried from the top and bottom of the cores; (4) further clarification on what types of units were used. The term soil-moisture block is generally referred to those units encased in plaster of Paris. Those units in metallic cases such as the Colman fiberglas unit or the original Bouyoucos nylon unit are generally referred to as soil-moisture

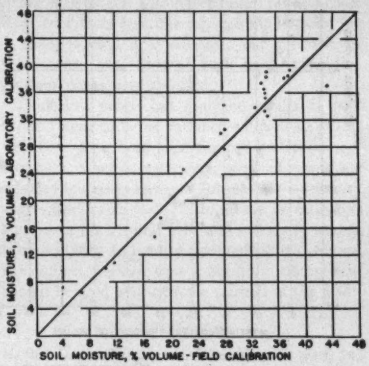
SOIL MOISTURE, % VOLUME - LABORATORY CALIBRATION
SOIL MOISTURE, % VOLUME - FIELD CALIBRATION
0 4 8 12 16 20 24 28 32 36 40 44 48
4 8 12 16 20 24 28 32 36 40 44 48

FIG. 2—Comparison of field and laboratory calibrations of fiberglas-gypsum blocks on Keene silt loam, 0–7 inches

units. (The later Bouyoucos nylon unit was encased in a gypsum block.) It was not clear in Remson and Fox's paper which units were encased in gypsum and which were not. Gypsum is believed to be the most suitable material to convey the moisture changes of the soil to a measuring instrument. It appears from the data that the authors did not use fiberglas-gypsum blocks such as those developed at Coshocton [*Youker* and *Dreibelbis*, 1951].

Remson and Fox should be commended for releasing the data they obtained because, as they say, "There is a need for appraisal of the performance of the blocks in different studies." It would be helpful if they would clarify the points mentioned above and confine their conclusions to the soil and specific techniques employed by them.

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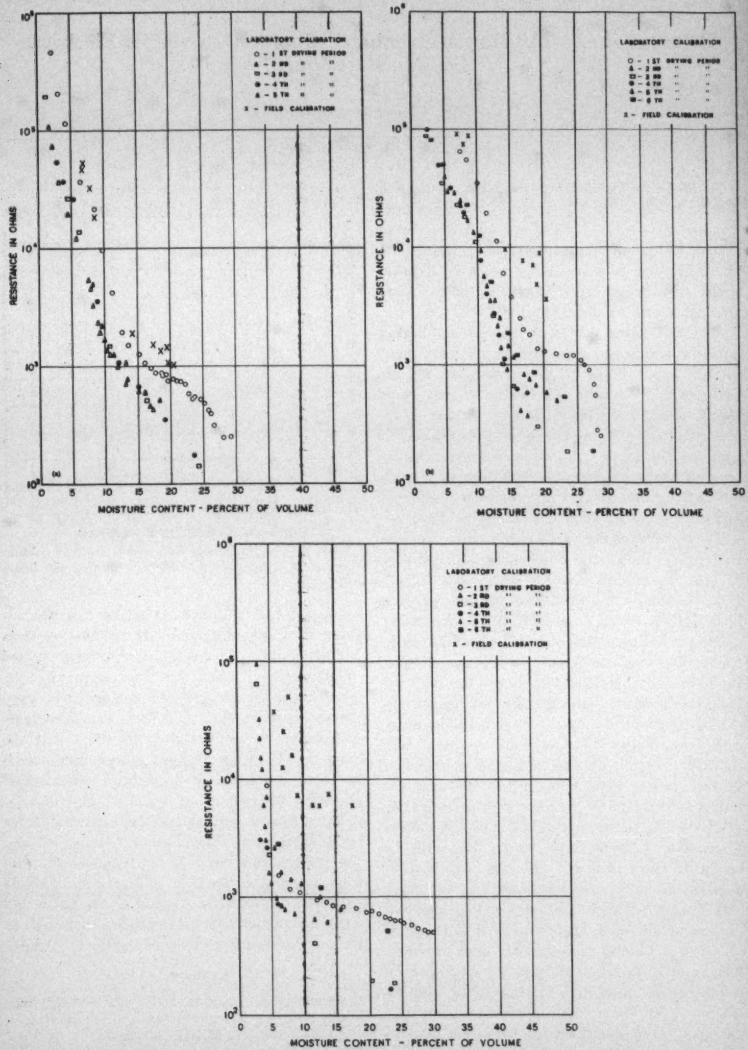

FIG. 3 – Corrected calibration curves for resistance units, (a) for the fiberglas unit for the ½-foot level; (b) for the nylon unit for the ½-foot level; (c) for the nylon unit for the three-foot level; the open symbols indicate the use of irrigation water, and the solid symbols indicate the use of distilled water

Irwin Remson (U. S. Geological Survey, Seabrook Farms, N. J., Author's closure)—An error translated the field calibration curves for the Seabrook soil-moisture units farther to the right than they should have been and caused the large moisture contents criticized by Dreibelbis. When properly recomputed, a few of the field curves coincide with the laboratory curves; a few are displaced to the right of the laboratory curves in their wetter portions and coincide with them in their drier portions; but most of the field curves, such as those in Figures 1abc, which have been redrawn as Figures 3abc, are still displaced to the right of the laboratory curves. The original conclusions remain unchanged except that the displacements are not present in all cases and the magnitudes of the displacements are more in accord with those found by other investigators [*Hendrix* and *Colman*, 1951; *Bethlahmy*, 1952; *Carlson*, 1954; *Horton*, 1955; *Lull* and *Reinhart*, p. 19, 1955].

The writers agree with Dreibelbis that their techniques with the Seabrook soils were largely responsible for the lack of agreement between the laboratory and field curves. As discussed by the writers and by others [*Carlson*, 1953; *Edlefsen* and *Anderson*, 1942], it is believed that such discrepancies result mainly from equilibration problems with the relatively large soil cores. It may be significant that most of the other investigators who reported differences between their laboratory and field curves also used soil cores [*Bethlahmy*, 1952; *Carlson*, 1954; *Horton*, 1955; *Lull* and *Reinhart*, p. 19, 1955]. The equilibration errors might not have occurred if smaller samples had been used [*Kelley*, 1944]. However, other errors might have been introduced by the unavoidable disturbance of bulk density and structure in the smaller samples [*Hendrix* and *Colman*, 1951].

Some displacement between the laboratory and field curves may be attributable to hysteresis. The units dry from a state of saturation in the laboratory. They either become wet or dry from a moisture condition other than saturation in the field. Thus, at similar tensions, the units in the field may have higher resistances than in the laboratory because at the same tension, a granular material may be less moist if it is being wetted than if it is being dried [*Baver*, 1948, p. 215; *Tanner* and *Hanks*, 1952]. This phenomenon is shown by those Seabrook units, especially plaster of Paris units, whose curves are horizontal in the wetter ranges so that resistance is independent of moisture content. In almost every case, this segment of the field curve lies above the corresponding part of the laboratory curve. In addition, curves that are displaced only in their wetter portions, also reported by *Horton* [1955], may be partly explained in this fashion.

In reply to Dreibelbis' questions concerning the calibration techniques used at Seabrook: (1) Temperature corrections were made for all readings. (2) Sampling was done in triplicate using either open-side or Veihmeyer tubes. (3) Soil cores were dried from both the top and the bottom. (4) A fiberglas unit, a nylon unit, and a plaster of Paris block were used at each level. Fiberglas-gypsum blocks were not used.

Dreibelbis points out that the results at Seabrook "seem to be at variance with investigators who have long been studying soil moisture. . . ." However, other investigators, some of whom are referred to above, have not found their laboratory curves applicable in the field. Some investigators have even found their field calibrations to change [*Taylor*, 1955]. In light of this conflicting evidence, the writers believe that laboratory calibrations should be used with extreme caution in the field.

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Discussion of "A Graphical Solution of the Flood-Routing Equation of Linear Storage-Discharge Relation"

BY J. E. NASH AND J. P. FARRELL

[Trans. 36, 319–320, 1955]

Charles D. Hopkins, Jr. (Tulsa River Forecast Center, U. S. Weather Bureau, Tulsa, Oklahoma)—The authors are to be congratulated on the presentation of a simple routing method that is, perhaps, more useful than they conceived.

The authors' fundamental assumption that $S = KO$ is, of course, a special case of the assumption made by *McCarthy* [1940] that $S = K\,[xI + (1 - x)]\,O$, where x is assumed to be zero. It is, as they state, the storage equation of a reservoir.

A river reach and a reservoir are, of course, not equivalent. The inflow term in the McCarthy storage equation represents the introduction of 'wedge storage,' but as such does not represent the fundamental physical difference between a river and a reservoir. The actual difference is that what occurs in a river is partly uniformly progressive flow or translation.

It is generally recognized in the literature that the movement of the flood wave in some streams is primarily translatory in nature. This is generally followed by a solution for McCarthy's K and x, an extremely futile and misleading procedure since routing of the inflow hydrograph by those constants will not reproduce the outflow hydrograph adequately.

In a stream channel, neither translation nor storage singly but rather a combination of the two acting jointly affect a hydrograph. Some channels, of course, are close enough to one extreme or the other to be considered as relatively pure cases.

It has been pointed out by *Clark* [1945] that the two elements of translation and storage can be considered separately in reproducing the hydrograph of a river basin. The equivalent of this in reach routing is what is known as 'lag and route.' There has been no particular notice taken of this practice in the literature, probably because of its simplicity. It can be said that the procedure consists of assuming that, instead of $S = f(I_0, O_0)$, $S = f(I_{t-}, O_0)$, t being the lag time.

As far as the wedge storage term is concerned, the writer is unconvinced of its practical utility. The substitution of wedge storage for the translatory effect can result in serious error. When large values of K and x are used together, a rapid increase in inflow will cause the computed outflow to decrease; that is, of course, a completely fallacious effect. The writer has made a cursory inspection of the maximum values of x that might be used with various values of K with the results as shown in Table 1.

TABLE 1 – *Suggested maximum x Values*

K	x
hr	
6	0.3
12	0.2
24	0.1
48	0.05
>48	<0.05

Whether these values are adequate depends partly on the character of the inflow hydrographs. But certainly, the amount of wedge storage that can be used is small, and the writer believes that very little gain in accuracy is obtained by such limited use.

In any event, a good practical method of river routing is to determine the lag and K (letting x equal zero) that will reproduce a certain reach. Then templates can be used to route the inflow hydrograph and the routed hydrograph then lagged. This whole operation can be performed on a single sheet. The only thing to be kept in mind in the use of the template, in addition to the authors' instructions, is that, in routing hydrographs, it must be assumed that $I_1 = I_{0-2}$. Then the template relates O_0, I_1 and O_2. In other words, starting at a fixed point in time, with the time base line set at an inflow n hours later, the template will then relate the initial outflow and the outflow $2n$ hours later. The inflow is reduced to a bar graph with the ordinates of the bars equal to the inflow at the midpoint of the period; furthermore, if the template is made of some transparent material, it is a simple matter to use the average flow for the routing period instead of the midpoint of the routing period in the event that the inflow hydrograph is quite irregular. This average flow can be determined by eye in the vast majority of cases.

The writer concurs with the authors that the method is rapid, accurate, and easy of application. The templates are easy to reproduce in any desired number to any desired time scale. And once the templates are made available, the method is reliable; that is, it is not subject to the possibility of breakdown inherent in more complicated mechanical or electronic devices. Therefore, he would suggest that the method has great merit for application to river forecasting.

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Discussion of "New Solution of the Inverse Shoran Problem"

by Clair E. Ewing

[*Trans.* **36**, 943–946, 1955]

P. M. Pepper (Mapping and Charting Research Laboratory, Ohio State University, Columbus 10, Ohio)—Equations (1) and (2) of Ewing's paper give formulas for the chords c_1 and c_2. The observation that these two quantities are used only in (7) and in combination as the product c_1c_2, leads to the following relation

$$c_1c_2 = 4 \sin^2 (\Delta\lambda/2) R_{p_1}R_{p_2}$$
$$= 2[1 - \cos \Delta\lambda]R_{p_1}R_{p_2} = 4R_{p_1}R_{p_2} \text{ hav } \Delta\lambda$$

with the consequential simplification in computation. The necessity of halving the angle $\Delta\lambda$ is eliminated, and the operations of forming the two products required by (1) and (2) and combining them are replaced by the computation of a single continued product.

Reviews, Abstracts, and Bibliography

Reviews and Abstracts

U. S. HYDROGRAPHIC OFFICE, *Instruction Manual for Oceanographic Observations*, H. O. Pub. no. 607 (2nd ed.), 210 pp., 1955, $12.00.

In the second edition of this work the authors have evidently had three objectives: to put it in a more sturdy volume on good paper, in loose-leaf form with proper table of contents; to add sections on some of the newer instruments; and to prepare a volume which could be used by many other people and organizations as well as the two oceanographic research vessels for which the first was intended.

The volume is concise and clear and arranged for easy reference. It is well illustrated and has a bibliography. The loose-leaf form will be useful since addenda can be placed in proper order.

The new sections describe the use of the geomagnetic-electrokinetograph, the electric wave staff, and the Spilhaus-Miller sea sampler. Doubtless more will be forthcoming soon. I would particularly like to see something on the measurement of currents by drogues.

In preparing the work for use by civilians the authors have been quite successful. Most of the text pertinent only to formal naval procedures is gone, and the remainder is concerned strictly with the technical procedures and is at once useful for almost any institution making expeditions at sea. There has been a great need for such a work.

The volume contains excellent sections on making Nansen bottle casts, drawing the water samples, recording the data, correcting the reversing thermometers, and computing the depth of the bottles.

The sections on chemistry describe salinity and dissolved oxygen determinations only. They are very clear and complete and are considerably helped by the illustrations included.

As to the details of preparing the graphs and profiles, the methods described here might be called classic rather than modern, but they are certainly adequate for shipboard use. It is not the purpose of the manual, of course, to enter into details of interpretation but rather into the proper preparation and presentation of the data, and this end is achieved. The instructions for taking and recording sonic depth measurements and for obtaining bottom sediment samples are clear. The section on obtaining biological specimens seems brief. Probably it will be most useful, however, when biologists ask for samples to be taken but do not go to see themselves to take them.

The procedures for sea, swell, and meteorological observations are well written and clear and may be of considerable use to the Hydrographic Office in getting comparable data from independent sources. In addition, there are samples of data sheets which would be of principal value to newcomers rather than to those running continuous programs. The book is well illustrated and contains many conversion tables. This volume is the most complete in the field today and is a valuable reference to have aboard any research vessel or at any shore facility where data are processed.

JOSEPH L. REID, JR.

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Notes and Personalia

Notes

APPLICATIONS FOR POSTDOCTORAL AWARDS—Applications will be accepted through September 4, 1956 for the second group of regular postdoctoral fellowships to be awarded by the National Science Foundation for the coming calendar year. The names of successful candidates will be announced October 16. Candidates must be citizens of the United States beginning or continuing study on the postdoctorate level. The stipend for fellowships is $3,400 a year plus allowances for married Fellows and a further allowance for travel, tuition, and fees. Applications should be sent to the Fellowship Office of the National Research Council, 2101 Constitution Avenue, N.W., Washington 25, D. C., or to the Division of Science Personnel and Education Office, NSF, Washington 25, D. C.

NEW COMMITTEE ON OCEANIC RESEARCH—The Executive Board of the International Council of Scientific Unions has authorized the organization of a Special Committee on Oceanic Research (SCOR). Roger R. Revelle has been named President, Bruun of Norway and Zenkovich of the USSR as Vice Presidents, and Hill of England as General Secretary. Appointment of eight additional members to the Committee is to be made from nominations offered by the interested

Unions. The Committee is instructed to organize national committees and plan a five-year program of oceanic research begin actual operations about 1960. The Committee will collaborate closely with UNESCO Committee on Marine Sciences.

EXPEDITION OF THE SCRIPPS INSTITUTION OF OCEANOGRAPHY—Expedition Chinook of the Scripps Institution of Oceanography is now under way in the area of northern Pacific lying between the Hawaiian and Aleutian Islands. The R/V *Spencer F. Baird* and the R/V *Stranger* will participate. The purpose is to collect data on bottom structure, bottom topography, properties of the water, and ambient noise level. The chief investigator is Roger Revelle with George G. Shor as scientific leader of the expedition. The project is sponsored by the Office of Naval Research and the Bureau of Ships of the U. S. Navy.

RUSSIAN TRANSLATION PROGRAM OF THE NATIONAL SCIENCE FOUNDATION—The National Science Foundation plans to expand its translation service in Russian scientific literature to include mathematics and biology, geophysics and other Earth's sciences, and the engineering sciences. Already an extended program is under way with respect to physics through arrangements with the American Institute of Physics.

FALL MEETING OF URSI TO BE HELD IN BERKELEY—The Fall Meeting of the U. S. National Committee of URSI is to be held in Berkeley, California, October 11 and 12, 1956 with Commissions 2, 3, and 4 planning scientific sessions. Interested persons should write to John P. Hagen, Secretary of the Committee at the Naval Research Laboratory (Code 4100), Washington 25, D. C.

NEW MEXICAN PUBLICATION IN GEOPHYSICS—A new publication, *Anales del Instituto de Geofisica*, is now being published by the Institute at the University of Mexico. Volume 1 (158 pages) dated 1955, has recently arrived; and items from it appear in the bibliography elsewhere in this issue.

CONTINUING GREENLAND EXPEDITION—Five scientists under the leadership of Thomas M. Griffis of the University of Denver have returned to their camp site of last summer on the icecap of Greenland. The expedition expects to remain until September 5. The camp is about 30 or 35 miles inland from Thule. The project is sponsored by the U. S. Army Corps of Engineers.

MEETING OF GULF COAST GEOLOGISTS—The sixth Annual Meeting of the Gulf Coast Association of Geological Societies will be held at the Plaza Hotel in San Antonio, Texas, from October 31 to November 2, 1956. Interested persons should get in touch with J. E. Glover, Publicity Committee Chairman, 1417 Milan Building, San Antonio 5, Texas.

NEW OFFICES OF CARL A. BAYS—Carl A. Bays and Associates, Inc., Urbana, Illinois, has opened an office in Hot Springs, South Dakota. This firm of industrial consultants will offer services especially in geology, geophysics, mining, petroleum, and engineering fields to serve clients in the Dakotas and the states to the West.

NEW MAPS AND OTHER MATERIALS OF THE U. S. GEOLOGICAL SURVEY—The following maps are now available: Preliminary geologic map of the Chalky Buttes area, Slope County, North Dakota, showing lignite beds, 24 by 27 inches, scale 1:31,680, 50 cents; Stratigraphy and photogeology of the southwestern part of Uinta Basin, Utah, oil and gas producing area, 41 by 54 inches, scale 1:63,360, $1.50; Geologic map of the Eastern Beaver Divide-Gas Hills area, Wyoming, 31 by 51 inches, scale 1:63,360, 50 cents; maps of eight metropolitan areas (Duluth, Minn.; Hartford, Conn.; Bridgeport, Conn.; Rochester, N. Y.; Cleveland, Ohio; Youngstown, Ohio; Knoxville, Tenn.; and San Diego, Calif.) 7½-minute quadrangles, $1.50, except Bridgeport and Knoxville $1.00.

The following maps, reports, and other materials are available for inspection at various Geological Survey libraries: Records of drilling in Dubuque County, Iowa, 1955; Reconnaissance geologic map of the St. Regis-Superior area, Mineral County, Montana; Seismic survey of Maynard Ordnance Test Station, Massachusetts; Geochemical study of soil contamination in the Coeur d'Alene District, Idaho; U. S. Geological Survey Exploration Program in the Trixie area Utah County, Utah (giving drilling results).

NEW RESEARCH VESSEL—The Woods Hole Oceanographic Institution has recently acquired the U. S. Coast Guard Cutter *Crawford* to be used in hurricane research. The ship recently underwent extensive renovation at a cost of $400,000. The tropical area between the Cape Verdes and the Caribbean where hurricanes are believed to form is usually avoided by science research vessels during the summer months. This will be one of the areas in which this ship will work. The ship is 125 ft long, 23 ft in width, and draws 9½ ft of water. It is diessel-powered with twin 500 HP engines with fuel capacity for 6000 miles at speed of 12 knots. It has been especially equipped for the hurricane work. The special equipment includes the continuously operated motion camera which will photograph the sea by exposing one frame every second and sensitive temperature measurements to observe minute changes in sea temperature as well as radio-sonde balloons.

Personalia

HARVEY O. BANKS, Acting State Engineer of California, has been named Director of California's new Department of Water Resources with headquarters in Sacramento.

NIELS C. BECK has left his position temporarily with the Armour Research Foundation of the Illinois Institute of Technology in Chicago and is now Director-General of the Union of Burma Applied Research Institute in Rangoon.

LLOYD V. BERKNER, President of the Associated Universities, Incorporated, and Vice President of the American Geophysical Union, was recently awarded an honorary degree of Doctor of Philosophy by the University of Uppsala, Sweden.

MAX C. BREWER of the Geophysics Branch of the U. S. Geological Survey with headquarters in Menlo Park, California, has been appointed Director of the Arctic Research Laboratory at Point Barrow, Alaska.

DETLEV W. BRONK, President, National Academy of Sciences and President, Rockefeller Institute, has been awarded an honorary doctorate by Cambridge University, England.

CHARLES R. BURROWS has left his work as Director of the School of Electrical Engineering at Cornell University and has joined the Ford Instrument Company, a division of the Sperry Rand Corporation. He becomes Vice President for Engineering.

ARNOLD COURT, who took his Doctor of Geography at the University of California in June, has joined the staff of the California Forest and Range Experiment Station with headquarters in Berkeley.

MAURICE EWING, Professor of Geology and Director of Lamont Geological Observatory, and President of the American Geophysical Union, has been elected to foreign membership by the Royal Netherlands Academy (Section for Sciences).

LAWRENCE M. GOULD, President of Carleton College, has been appointed by President Eisenhower to a second six-year term on the National Science Board.

WILLIAM C. LAMB has left Gulf Oil Corporation, Tulsa Production Division, to become the Division Geophysicist of the Foreign Exploration Division of the Gulf Oil Corporation with headquarters in New York.

ROBERT H. LYDDAN, Regional Engineer for the U. S. Geological Survey on topographical work, has been appointed Assistant Director of the U. S. Geological Survey.

CARLOS S. OSPINA, member of the firm of Olarte, Ospina, Arias, and Payan, Ltd., Bogata, Colombia, has been awarded the National Engineering Prize for 1956 by the Colombia Society of Engineers for his reporting on the development of power in the Guadalupe River basin.

ALFRED C. REDFIELD, Associate Director of the Woods Hole Oceanographic Institution and Past President of the Section of Oceanography of AGU, has been appointed an honorary member of the Marine Biological Association of the United Kingdom. During the coming winter he will devote considerable of his time to work at the Scripps Institution of Oceanography. He was also awarded an honorary doctorate by the University of Oslo in March, 1956.

GERHARD F. SCHILLING of the National Academy of Sciences, who has been Program Officer of the U. S. National Committee for the International Geophysical Year since December 1954, has been appointed to the staff of a study project concerned with planning the establishment of a World Data, Analysis, and Publications Center for the United States International Geophysical Year program.

PIERRE TARDI, Geographer Inspector General, Professor at the Ecole Polytechnique, and Director of the Central Bureau of the International Association of Geodesy, has been elected a member of the French Academy of Sciences in the Section of Geography and Navigation.

E. H. VESTINE, on leave of absence from the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, will head a staff study at the National Academy of Sciences to survey and analyze the possibilities of establishing a United States World Data, Analysis, and Publications Center as well as disciplinary data archives and analysis units for the International Geophysical Year program.

THEODORE VON KARMAN of the California Institute of Technology was recently given the Presidential Medal of Freedom, the highest honor for an American civilian, for his outstanding work in aerodynamics. The award was made by Lt. Gen. Donald L. Putt of the Air Force's Air Research and Development Command on behalf of President Eisenhower.

WARREN WEAVER, Director, Division of Natural Sciences of the Rockefeller Foundation, has been appointed by President Eisenhower to the National Science Board to fill the unexpired term of the late James B. Macelwane.

JOHN T. C. YEN of Philadelphia, a research geologist, is touring western Europe to study the characteristics of invertebrate assemblages of standard sections of Mesozoic and Tertiary formations.

WALTER SYDNEY ADAMS, Director of the Mount WILSON OBSERVATORY from 1923 to 1946, died in Pasadena, May 11, 1956 at the age of 79. He was born in Syria. He took his baccalaureate degree from Dartmouth College in 1898 and his master's degree from the University of Chicago in 1900. He was awarded doctorates by Dartmouth, Pomona, Columbia, University of Southern California, University of Chicago, and Princeton. He began his professional work at Yerkes Observatory in 1901, and in 1904, upon the establishment of the Mount Wilson Observatory, he took up duties there, where he spent the rest of his professional career. He became a member of AGU in 1930.

SAMUEL JACKSON BARNETT, Emeritus Professor of Physics at the University of California at Los Angeles, died May 22, 1956 at the age of 82. He was born in Woodson County, Kansas, took his baccalaureate degree at the University of Denver in 1894, did graduate work at the University of Virginia, and took his doctorate from Cornell University in 1898. He began his professional career in teaching at the University of Denver in 1894. He also taught at the University of Virginia and Cornell University while there as a graduate student. Subsequently he taught physics at Colorado College, Stanford University, Tulane University, and Ohio State University, and in 1918 began an eight-year tour of duty with the Carnegie Institution of Washington. He began his work at the University of California in 1926 and became professor emeritus in 1944. He was a Research Associate of the California Institute of Technology He was a member of the National Academy of Sciences and had been a member of AGU since 1920. He was one of the original members of AGU.

WILLIAM FREDERICK FOSHAG, Mineralogist and Head Curator of the Department of Geology of the National Museum, Smithsonian Institution, died May 22, 1956 at the age of 62. He was born at Sag Harbor, New York, and took his baccalaureate degree at the University of California in 1919 and his doctorate from the same school in 1923. He entered the service of the National Museum in 1919 and was connected with the expedition to Mexico in 1926, 1927, 1929, 1931, and 1941–45, Japan in 1946, and Guatemala in 1949. He served as President of the Mineralogical Society and at the time of his death he was President of our Section of Volcanology, Geochemistry, and Petrology. He was active in volcano research and had first-hand knowledge of the life history of Paricutin Volcano in Mexico. He had been a member of AGU since 1944.

EDWIN RUSSELL LLOYD, Consulting Geologist and Petroleum Engineer, died February 14, 1955 at the age of 72. He was born at Lloydsville, West Virginia,

took his baccalaureate degree at Ohio Wesleyan University in 1905, and was elected a Rhodes Scholar at Oxford University in 1908. He continued his graduate studies at the University of Chicago. From 1911 to 1917 he served with the U. S. Geological Survey and after a brief tour of duty in commercial work returned for a year to the Geological Survey. In 1919 he again returned to commercial work and in 1923 set up a consulting practice as a geologist. He had been a member of AGU since 1945.

GEORGE ERNEST MERRITT, who retured in January 1956 from his duties as physicist at the Naval Proving Grounds in Virginia, died July 5, 1956 at the age of 66. He was born in Indianapolis and took his baccalaureate degree, later pursuing graduate work at the University of Wisconsin, Cornell University, and George Washington University. In 1917 he took up duties with the National Bureau of Standards where he served until 1923. At that time he began four years of work with the U. S. Coast and Geodetic Survey. From 1937 to 1947 he was at Bendix Aviation Corporation. He entered the service of the Naval Proving Grounds in 1947. He had been a member of AGU since 1932.

JERRY NELSON, who was engaged in geophysical work with the Shell Oil Company with headquarters in Houston, Texas, on leave for duty with the Air Force, was killed in an air crash on February 20, 1956 at the age of 23. He received his baccalaureate degree from Rensselaer Polytechnic Institute in 1954 and immediately entered upon duties with Shell Oil Company. In July 1955, he began service as Second Lieutenant in the Meteorological Branch of the Air Force. He had been a member of AGU since 1954.

JOHN LYON RICH, Professor of Geology at the University of Cincinnati, died May 21, 1956 at Logan, Ohio, at the age of 72. He was born at Hobart, New York, took his baccalaureate degree from Cornell University in 1906, his master's degree in 1907, and his doctor's degree in 1911. He began his professional career by teaching at Cornell University while he was a graduate student and from 1911 to 1918 was engaged in teaching at the University of Illinois. He worked in the petroleum industry as a geologist from 1919 to 1931. He entered upon his duties at the University of Cincinnati in 1931. He had been a member of AGU since 1936 and only last fall was one of the AGU delegates to the meeting of the U. S. National Commission on UNESCO which was held in Cincinnati.

ROBIN EGERTON SPENCER of the U. S. Weather Bureau died June 3, 1956 at the age of 59. He was born at Ogden, Utah, and received his higher education through extension courses and night classes at George Washington University and Graduate School of the U. S. Department of Agriculture. He entered the Weather Bureau in 1919 and also served as the Assistant Chief of the Climatological Services Division at the time he died. In addition to his science work he is well known as a writer, his best known work perhaps being *The Lady Who Came to Stay*. He had been a member of AGU since 1939.

MOULTRIE ALFRED WARREN, Project Engineer for the U. S. Geological Survey on water-resources work, died April 30, 1956 at the age of 43. He was born at Byron, Georgia, and took his baccalaureate degree in Georgia School of Technology in 1937. He worked for about a year at the U. S. Waterways Experiment Station and in 1938 took up his duties with the U. S. Geological Survey. He became a member of AGU in 1941.

Union, Section, and Committee Activities

Minutes of Executive Committee Meeting, American Geophysical Union

First Session, April 29, 1956

The meeting was called to order in the Board Room of the National Academy of Sciences—National Research Council Building, 2101 Constitution Avenue, Washington, D. C., by President Maurice Ewing at 14h 07m.

Present—Thirty-four persons were present as follows: L. H. Adams, W. W. Atwood, Jr., K. Hilding Beij, L. V. Berkner, Francis Birch, Ralph R. Bodle, Walter H. Bucher, J. J. Capello, Felix Chayes, Maurice Ewing, Jno. A. Fleming, W. F. Foshag, R. E. Gebhardt, Ross Gunn, Ross R. Heinrich, Harry H. Hess, W. E. Hiatt, Albert J. Hoskinson, P. M. Hurley, Woodrow C. Jacobs, H. R. Joesting, J. W. Joyce, Walter D. Lambert, H. E. Landsberg, Ray K. Linsley, Thomas F. Malone, James A. Peoples, Jr., Charles Pierce, A. Nelson Sayre, Waldo E. Smith, Kirk Stephenson, Victor Vacquier, H. G. Wilm, and James T. Wilson.

President Ewing noted that he felt very sad occupying the chair of the presidency because it brings to mind the loss of President Macelwane on February 15, 1956, and General Secretary John Marble on June 6, 1955. He noted that the Union has lost two very good friends in these deaths.

President Ewing also noted the fact that Honorary President John Fleming was with us, having returned to Washington in December, 1955, after about two years' residence in Nashville. He called on Honorary President Fleming for remarks, who noted that he is appreciative of the new format of the *Transactions*.

Approval of minutes—The minutes of the Executive Committee meeting held on October 15, 1955, published in the December, 1955, issue of the *Transactions* (pp. 1107–1118), were approved.

General Secretary's Report

The last report of the General Secretary was that of October 15, 1955, published in the December issue of the *Transactions* (pp. 1107–1111).

On February 15, our President, James B. Macelwane, died. Subsequently the Executive Committee took formal action to designate Maurice Ewing as his successor to fill the unexpired term. At the same time steps were taken to designate as Vice President the person elected as Vice President for the triennium beginning July 1, 1956. Lloyd V. Berkner was elected Vice President and so is now considered to be Vice President filling the unexpired term of Maurice Ewing, as well as the regular three-year term beginning next July 1.

In connection with President Macelwane's passing, we received a number of communications from individuals and organizations in this country and abroad. Among these was a resolution formally adopted by the Executive Committee of the U. S. National Committee for the IGY which read: "The U.S. National Committee for the International Geophysical Year notes with deep regret the recent death of the Reverend James B. Macelwane, S.J., who has been for many years one of the country's leading geophysicists, and who has recently so ably assisted the Committee in its planning of the United States program for the International Geophysical Year. Father Macelwane has served as Chairman of the USNC-IGY Technical Panel on Seismology and Gravity Measurements, and the development of sound and comprehensive programs in these fields can be attributed in large measure to his abilities, interests, and wisdom. His scientific counsel and mature judgment will be missed not only by the Committee in the furtherance of the United States program for the International Geophysical Year but by the entire scientific community; and his remarkable personal qualities—his kindness and patience, his warmth and friendliness—will always be remembered by those who had the privilege of knowing and working with him."

Publications—The following *Transactions* have been printed and distributed since our last meeting:

October 1955: 184 numbered pages and 8 unnumbered pages including 7 pages of paid advertising; edition, 6100

December 1955: 194 numbered pages and 8 unnumbered pages including 7 pages of paid advertising; edition, 6100

February 1956: 134 numbered pages and 12 unnumbered pages including 7 pages of paid advertising; edition of 6300 (beginning of letterpress format)

April 1956: 127 numbered pages and 12 unnumbered pages including 10 pages of paid advertising; edition of 6200

The Editorial and Publication Committee, as you perhaps noted by the February issue of the *Transactions*, settled pretty well on the general format for the *Transactions* by letterpress. A number of details are still in a state of flux, and it is anticipated that additional minor changes will be made during the year and at the end of the year.

Shortly before President Macelwane became so seriously ill that he could no longer attend to matters, he prepared the final draft of a statement of progress that went forward to all members at the beginning of this year. The response to the change in format has been gratifying. There have been many commendatory letters, and I believe none took serious issue with this change.

Last year we received a grant from the National Science Foundation of $4000 to help us get caught up on our backlog in an effort to publish papers within six months of their receipt. We were successful in getting caught up, perhaps expending somewhat more than the $4000 grant, but we have obtained a situation such that a paper received in such shape that it does not require return to the author is now ordinarily published in about six months. We are hopeful that we may maintain this.

Membership—Membership data are:

Membership, October 10, 1955	4974	
New members, October 11, 1955 to April 25, 1956, including 100 applications in process	207	5181
Resigned (also 7 transferred from tentative dropped figure of 136 reported October 15, 1955)	120	
Inactive	4	
Deceased (reported since October 15)	17	141
Membership as of April 25, 1956		5040

Since the first of the year there has been an increasing number of membership applications, partly as a result of increased activity on the part of the Membership Committee and partly because of an increase in the number of spontaneous applications. It is hoped that both of these may continue and that our membership will again begin to increase substantially. Since the first of the year we have accepted or have in progress 36 applications for student membership. This would appear to be a healthy development.

The following 17 deaths have been reported to the Union office since our last meeting: Paul Vincent Hodges, February 24, 1955; Gerrit Duys, Jr., March 16, 1955; Eric Hinton, May 7, 1955; Jose Garcia Montes, June 24, 1955; Nicholas Anthony Rose, July 16, 1955; Isaac Monroe Cline, August 3, 1955; C. Leland Horberg, August 18, 1955; Neal J. Heines, August 20, 1955; Arthur D. Butterfield, August 22, 1955; Frank Morris Cowell, October 11, 1955; William Grant, October 14, 1955; Robert K. Souter, November 18, 1955; Henry C. Stetson, December 5, 1955; Roy Waldo Miner, December 13, 1955; Ludger B. Mintrop, January 1, 1956; James B. Macelwane, February 15, 1956; Edward A. Colman, March 20, 1956.

Dues unpaid—Owe for 1956		1024
Partly paid 1956		103
Owe for 1955 and 1956		209
Partly paid 1955 and for 1956		7
Owe for 1954, 1955, and 1956		192
Partly paid 1954, for 1955, and for 1956		5

It is required that the 197 who have not paid their dues in full for 1954 and subsequent years be reported with the recommendation that they be dropped from membership. As is customary, the further recommendation is made that the office be instructed to make an additional effort to get them to return to good standing. In previous years, this effort has been quite successful.

Finances—Below is a brief statement of our assets as of April 1, with comparison for the last two years.

	April 1, 1956	April 1, 1955	April 1, 1954
Cash balance	$30,424	$24,459	$21,742
Permanent Fund	12,834[a]	11,573[a]	8,000[a]
Emergency Fund	1,000	1,080	1,043
T. M. and E. Award Fund	985	465	210
	$45,243	$37,577	$30,995

[a] Does not include interest on $2,368 of U. S. Savings Bonds.

Detailed figures for the past year are available for inspection. See also report of the Budget Committee to be presented later and the report of the Committee on Audit published in the December, 1955, issue of the *Transactions*, pp. 1116–1118.

Elections—Elections by mail ballot were held during the month of March and tabulated by a Special Committee of Tellers under the chairmanship of Harry S. Ladd. The Committee will report later.

Statutes and By-Laws—At the meeting on October 15, 1955, steps were taken to make some adjustments in the Statutes and By-Laws. The Statutes can only be changed by mail ballot of the membership, and with the approval of the National Research Council. Article 3(a) of the Statutes has accordingly been modified to read as follows:

Members in good standing for a total of 25 years (or 15 years for members joining before January 1, 1946) shall, following retirement from active professional service because of age or disability and upon written notice to the General Secretary, be extended the complete privileges of membership without further payment of dues. The Executive Committee may also extend these privileges to members for extraordinary services to the Union.

Also the ~~first~~ step was taken to modify By-Law (18) as follows:

By-Law (*18*)—The General Secretary elected by the Union shall be responsible to the Executive Committee of the Union for the general administration of the Union's activities as determined by the Executive Committee of the Union. He shall serve without honorarium, and shall exercise general supervision over the Executive Secretary. He shall serve as Treasurer of the Union, receive and disburse funds in accordance with the instructions of the Executive Committee of the Union, sign checks as General Secretary on the accounts of the American Geophysical Union with depositories approved by the Executive Committee of the Union, and shall provide a surety bond in a sum set by the Executive Committee of the Union and at the expense of the Union, for funds of the Union under his control. If the General Secretary is absent or incapacitated, the President, or, if he is absent or incapacitated, the Vice-President, shall sign checks against the Union accounts. The General Secretary, or the President or the Vice-President serving as Treasurer in his capacity, may empower the Executive Secretary to sign checks against the accounts of the Union during their terms of office. The President, Vice-President, and the Executive Secretary shall furnish surety bonds in the same manner and amount as the General Secretary.

These changes are essentially to provide ~~means~~ means whereby the General Secretary might, if he deemed it advisable, designate the Executive Secretary as a signator on checks against the accounts of the Union. Under the existing Statutes action is at one meeting of the Executive Committee, notice of this action is subsequently published, and then within a year confirming action is to be taken. Notice of intent to change this By-Law was published in the December issue of the Transactions, and it is to be recommended that final action be taken at this meeting.

Office staff and jobs—With the discontinuance of the composition of the *Transactions* in the office of the Union, one position was abolished toward the end of 1955. The office staff now consists of James J. Capello Assistant to the Executive Secretary; Lois C. Baker, Clerk-Stenographer appointed on a temporary basis as of April 17, 1956; G. Consuelo Rodriguez, Clerk-Typist, appointment effective on a probationary basis March 28, 1956. Milena Vaneckova, Clerk-Typist, left our employ in December to marry, and Zdenka Dalecka, formerly Electromatic Operator, subsequently taking Miss Vaneckova's position as a Clerk-Typist, left on March 31 to take up other duties. During the first three months of the year we had the temporary serivces of Judith Holland, student at Antioch College, in connection with their work and study system. Glenda Quinn, who served as a full-time Clerk-Stenographer up to the beginning of school in 1955, continues on a part-time basis, and James F. Goldberg, a high school student who comes in after school, serves as office boy. The activities of the Union continue under the direct supervision of Waldo E. Smith, Executive Secretary.

Quarters—In mid-December we received word from the Carnegie Institution of Washington that the space we now occupy is needed for other purposes and the Executive Officer requested that we make arrangements to secure other quarters as soon as possible. Because this matter could not await the regular meeting of the Executive Committee, authority to seek new quarters at a cost not to exceed $3000 per year was obtained by mail ballot. A committee consisting of Earl Ingerson, A. G. McNish, and J. Wallace Joyce began investigating possible office space. In accordance with their recommendation, steps are being taken to secure quarters in the new building of the AAAS at 1515 Massachusetts Ave., N.W. We have reserved about 725 square feet at $4 per square foot per year. Steps are in progress to get permission to occupy these quarters from the Board of Zoning Adjustment of the D. C. Government. It is hoped that we may move to the new quarters about mid-June.

We are restricting our space to a minimum in these new quarters and do not plan to provide storage for the older issues of the back *Transactions*, and have entered into negotiations with Kraus Periodicals for them to take off our hands our stock of back numbers and to reprint out-of-print numbers so that complete sets will be available.

Back in 1939 special exhibit maps were prepared for use in connection with the Seventh General Assembly

of the International Union of Geodesy and Geophysics held in Washington. These 45 or 50 maps have been held here in a large flat file which will be too bulky to move to the new quarters. There is little demand for prints of these maps and it would seem that they are chiefly of historic interest. Accordingly, it is felt that steps should be taken to turn them over to some organization or some individual who has interest in their preservation and at the same time would be willing from time to time to provide prints to purchasers. Inquiry in this regard has indicated that perhaps these should best be placed in the hands of George P. Woollard, who was the chief contributor in their compilation. Authority will be requested to transfer these to him.

Air Force Contract—As noted under publications, work on the Air Force contract is scheduled to be completed by June 30. A request was made during the fall or winter for an amendment to the contract under which we had arranged the mechanics of the Conference on Chemical Aeronomy, but inasmuch as the scientific endeavor was to be left in the hands of another committee it was felt that we should not undertake this. (Incidentally we are interested in offering our services to facilitate scientific conferences provided the arrangements for the scientific aspects as well as others are under AGU guidance.)

Bibliography of Hydrology, 1951–1954—This work has been completed and the Bibliography in master copy for offset reproduction was turned over to the Bureau of Reclamation in December 1955. Publication has recently been completed by the Government Printing Office. This consists of some 2300 items occupying 207 pages.

International matters—There will be a subsequent report by the Chairman of the Committee on International Participation, and suffice it here to note that the Subcommittees of this Committee have been busy in the compilation of their reports which are now in the hands of the Committee Chairmen for collation and the preparation of a report which will recommend important changes in the setup of IUGG including a more permanent and better arrangement for financing.

The Eleventh General Assembly of IUGG will be held in Toronto Canada, September 3–14, 1957. We have offered our aid and support to the Canadians in this endeavor which they are undertaking somewhat belatedly after it developed that the meeting could not be held in Argentina in 1957.

The AGU has long felt that there should be an annual meeting of the Council of IUGG. This was underscored in President Macelwane's letter to General Secretary Laclavere on July 6, 1955. In February 1956, General Secretary Laclavere called such a meeting and scheduled it for April 1956. While we felt that we are at a disadvantage in this regard (1) in the matter of time and (2) with regard to having seen no agenda for the meeting, arrangements were made for J. Wallace Joyce to attend the meeting of the Council. He is due back today, April 29, and we are hopeful that he will be on hand to give us some word of this meeting.

Meetings—A meeting was held by the Pacific Northwest Regional Group at Portland, Oregon, November 17–18, 1955. Seventy-six registered and nine technological papers were presented at the two sessions of the meeting. The Group held a dinner meeting on the evening of November 17.

The Geophysical Society of Hawaii, which serves as the Mid-Pacific Regional Group of AGU, held a meeting in Honolulu, November 15–18, 1955, with 103 registrants. The meeting covered most all aspects of the broad fields of geophysics and was followed by field trips to points of geophysical interest.

The AAAS met in Atlanta, Georgia, between Christmas and the New Year, in 1955, and in connection with that attempts were made to develop a session in geophysics under an *ad hoc* committee chairmained by Werner A. Baum. It was finally decided that AGU should join forces with the American Meteorological Society in this meeting, and the two groups together arranged a program for a single session. In addition, however, AGU was one of the cosponsors of the Symposium on the International Geophysical Year which was a decidedly successful event at that meeting. The next meeting of the AAAS will be held between Christmas and New Year in 1956 in New York. The question is now, however, whether we should take part in this meeting by arranging one or more sessions in geophysics. The guidance of this Committee is requested.

The Pacific Southwest Group held its annual meeting at the University of California in Los Angeles, January 26–27, 1956, with about 100 in attendance. Sixteen papers were presented bearing chiefly on the hydrologic and meteorologic aspects of geophysics.

There are tentative plans for regional meetings to be held in the North Central Region possibly in St. Louis some time in the summer of fall, in the Pacific Northwest Region in the late fall, and in California probably at Sacramento or Davis in late January or early February 1957.

The Thirty-Eighth Annual Meeting will be held in Washington, D. C., in the week immediately following the meeting of the National Academy of Sciences scheduled for April 29–May 1, 1957. This makes the dates of our Annual Meeting May 6–8, 1957. (In mid-July, word came that the Academy meeting is to be held April 22–24, 1957. Our dates have accordingly been changed to April 29–May 1, 1957; see Special Announcements.)

National Research Council report—The report of AGU to NRC was completed and approved by the President in November 1955 and went forward to the Council shortly thereafter. This covered the period from July 1, 1954 to June 30, 1955.

Special delegates—John L. Rich and Lloyd V. Berkner served as special representatives of AGU at the meeting of U. S. National Commission on UNESCO held in Cincinnati in November 1955. We received an invitation to send a representative to the Golden Jubilee Celebration of the Mining, Geological, and Metallurgical Institute of India which was held in mid-January 1956. There seemed to be no one available on the ground who could be designated, so we were not represented at this function.

A meeting of the secretaries of the societies and organizations affiliated with the American Geological Institute was held in connection with the AAPG meeting in Chicago within the last week. Our secretariat was not represented. A meeting of the more formally organized Association of Engineering Secretaries is to be held in Cincinnati in July 1956. It has not yet been determined whether the Executive Secretary will attend this meeting. Our travel funds are so limited that there is always a question as to the purpose for which this fund might best be used. We have in hand

an invitation from the Air Research and Development Command for attendance at the Symposium on Geophysics to be held in Boston, May 22–23, 1956. This emphasizes the aerological aspects of geophysics.

An invitation has also recently come in to the General Secretary from the General Motors Corporation inviting him to attend the dedication of their technical Center on the outskirts of Detroit on Wednesday, May 16, 1956.

Situation in meteorology—An anonymous letter from a meteorologist came to AGU under date of November 23 discussing the apathy of most AMS members towards AGU membership. The fact is that in our membership, while we include many leading meteorologists, we do not include a very high percentage of the rank and file meteorologists as attested by the fact that AMS membership alone is about 5000 and only about 2000 of our members are affiliated with the Section of Meteorology. Copies of this letter were forwarded to the officers of the Section of Meteorology and to others, and while it has been quite adequately rebutted, the fact remains that we would like somehow to attract a larger percentage of the meteorologists to our membership.

Items of interest—Plans for a conference on the size and shape of the Earth under the joint sponsorship of the National Science Foundation and St. Louis University are progressing, although there has been some lost time due largely to the illness and death of Father Macelwane. More recent plans contemplated this might be held in September or October of this year.

A study on the role of basic data in the development of our land and water resources is being undertaken by the Conservation Foundation, and the services of two of our members (W. G. Hoyt and Walter B. Langbein) have been retained to give guidance to this effort.

A Conference on Theoretical Geophysics was held in Washington, February 1–3, 1956, under the sponsorship of the National Science Foundation and the Carnegie Institution of Washington. Some 60 or 70 persons participated in this three-day program, which adopted a number of resolutions for the establishment of one or more institutes of theoretical geophysics.

A bill has been introduced in the House of Representatives to establish an Institute of Geophysics at the University of Hawaii.

The Twentieth International Geological Congress will be held in Mexico from September 4 to 11, 1956.

The International Geographical Union will held its Ninth General Assembly and Eighteenth International Geographical Congress in Rio de Janeiro, Brazil, August 9–18, 1956.

A. NELSON SAYRE, General Secretary

Action on the General Secretary's report—The report was accepted.

Action on recommendations of the General Secretary—The recommendations of the General Secretary were approved that a further attempt be made to return to active membership those who owe dues tor 1954 and 1955, and that those who do not respond should be dropped from membership.

The change in By-Law 18, initiated at the last meeting of the Executive Committee and with formal notification of the proposed change published on page 1118 of the December, 1955, issue, to the effect that the General Secretary or other authorized officer might, if he deemed it advisable, designate the Executive Secretary as a signator on checks against the accounts of the Union, was approved. This is a final confirming action, and the change is now deemed to be in effect.

The General Secretary was authorized to transfer to George P. Wollard the 1939 Special Exhibit Maps prepared for the Seventh General Assembly of the International Union of Geodesy and Geophysics held in Washington in September, 1939.

Recommendation of the President—It was noted by the President that the By-Laws provide that the last Past President shall be a member of the Executive Committee. It was recommended that in this instance this be interpreted to mean the last living Past President and that Walter H. Bucher should be considered a member of this Committee during the coming triennium. A motion to this effect was approved.

Reports of Standing Committees

International Participation—Chairman Lloyd V. Berkner noted that, although the Committee has been active during the past months in the preparation of its recommendations and report relative to the International Union of Geodesy and Geophysics, it has had no formal meeting. It has been active in connection with working out arrangements for the next General Assembly of IUGG to be held in Canada; the present plans are that this will be held in Toronto, Canada, September 3–14, 1957. He noted that, perhaps at least in part in response to President Macelwane's letter of July 6, 1955, the General Secretary of IUGG called a meeting of the Bureau, Council, and Finance Committee which was held in Paris on April 17–21, 1956. No advance agenda was available for general circulation, but the topics for discussion were received a few days prior to the departure of J. Wallace Joyce for the meeting and it was possible to have had informal discussions and to make arrangements for Joyce's participation. Joyce gave a summary report of the meeting in Paris (see Appendix 1), which was accepted and referred to the Committee on International Participation for careful study.

Editorial and Publication—Chairman A. Nelson Sayre noted that this Committee has been very active in connection with problems concerning change in format of the *Transactions* and consideration of monograph problems. Plans for the publication of the Woods Hole Conference papers as Monograph No. 1 had to be dropped because prospective sales did not seem to be sufficient to indicate any possibilility of paying the cost and we were unable to secure any support from foundations to aid us in this. With regard to the Symposium on the Antarctic, it was recommended that we proceed with this on some basis. The Ford Foundation declined our application for a grant to get the monograph series under way, but the Committee on the Antarctic of the U. S. National Committee for the International Geophysical Year had indicated that it would recommend that the U. S. National Committee underwrite this so that it may be published promptly and that AGU will be saved from any possible loss by arrangements yet to be worked out. It was noted that the Committee on the Antarctic had indicated it would prefer that this not be published as a regular commercial publication. It was suggested, however, that the possibility of publication by one of the university presses be explored in this regard. The Executive Committee voted to set up a revolving fund

of $2500 to get this under way, with the understanding that arrangements be worked out with the U. S. National Committee for the IGY to hold AGU ultimately free of cost on Monograph No. 1.

Steps are being taken to compile an index for the *Transactions* from 1945, the beginning of the bimonthly issues, through 1955, the end of the format by offset printing. This work is proceeding under a revolving fund of $1500 established several years ago in connection with the index for the first 25 years.

Budget—Acting Chairman Robert E. Gebhardt, who worked out this budget during the spring months in the absence from the country of Chairman Beij, presented the report as set fourth in Appendix 2, which after considerable discussion was accepted.

Meetings—In the absence of Chairman John N. Adkins, it was noted that the Thirty-Eighth Annual Meeting is to be held on May 6-8, 1957. The question was also raised in the matter of joining with the AAAS in its meeting to be held in New York in later December. It is the understanding that the initiative in that regard must be taken by members in residence in that general area.

Membership—Chairman W. E. Hiatt asked for advice and ideas on how we can increase our membership, employing methods more effective than he has been using during the past two or three years. He noted that it is quite difficult to work with a Committee whose membership is scattered over the country, and that chiefly this has been a job for the Chairman or others who feel some sense of dedication to the job. He stated that letters have been written to all of the people who have been recommended by members on the slips sent with the dues notices. Kirk Stephenson mentioned that he had recently sponsored our youngest member, a 14-year-old high school boy, and he feels that this is not too early an age to begin to direct promising young people to the possibilities of geophysics and enlisting them as student members. P. M. Hurley felt that something should be passed out to seniors in geophysics at the various universities—perhaps just a sheet inferring that AGU is the organization to which all people going into geophysics should belong.

Reports of Special Committees

Cosmic-Terrestrial Relationships—In the absence of Chairman Harlan T. Stetson, a summary report was presented, which was accepted with the understanding that the full report would be published in the *Transactions*. (It appears subsequently under the heading of Reports.)

Award of William Bowie Medal—Chairman L. H. Adams noted that a selection had been made and is to be revealed at the evening session on May 1, 1956.

Tellers—In the absence of Chairman Harry S. Ladd, Kirk Stephenson presented the report which is printed on pages 384–385 of the June, 1956, issue.

Quarters—In the absence of Chairman Earl Ingerson, the Executive Secretary presented a summary of the report set forth in Appendix 3. This was accepted.

Reports of Sections

Meteorology—Secretary Woodrow C. Jacobs, in the absence of President Phil E. Church, noted the receipt of a report of the Committee on Cloud Physics which he recommended for publication (see Appendix 4).

Hydrology—President H. G. Wilm noted the recent passing of one of the active members of the Section, E. A. Colman. He also mentioned that the Section of Hydrology is participating in symposia on floods and ground water to be held in Dijon, France, September 20–26, 1956 under the auspices of the International Association of Hydrology. This is planned as a centennial celebration of classical work by Darcy.

National Academy of Sciences—National Research Council

International Relations—Wallace W. Atwood, Director of the Office of International Relations, noted that the Office is now in a position to be helpful to our Committee on International Participation because of a grant of about $80,000 per year received from the Ford Foundation for the next five years. He stated that this also facilitates further exchange of scientists by U. S. scientists going abroad and foreign scientists coming to this country as an aid in developing our international scientific program. He noted that in 1958 the United States is to be host at the next General Assembly of ICSU and that Berkner, as President of the Council, will be presiding on that occasion.

Affiliated Organizations

American Geological Institute—E. A. Eckhardt and H. R. Joesting are our two representatives on the Board of the Institute. Eckhardt sent in the report set forth in Appendix 5. There was extensive discussion of our relationship with the Institute, noting that we had approved the new Constitution on May 2, 1954, at the same time making certain recommendations that we requested be given consideration as indicated on page 689 of the August, 1954, *Transactions*. They each were turned down in the spring of 1955 with the implication that the Institute was to be strictly geological in its nature and outlook. The feeling was expressed, however, that we should seek out a firm understanding on these problems and that we should study means of being more helpful in AGI's problems, with the suggestion made that the budget for travel should be increased in order that the Executive Secretary might attend administrative sessions of AGI regularly. It was finally agreed that a committee be appointed to review the entire relationship with AGI and make recommendations in this regard.

American Association for the Advancement of Science—General Secretary Sayre and Werner A. Baum are currently our two representatives on the Council of the AAAS. The question was raised concerning a suggestion of AAAS that each affiliated organization contribute $25 for each of its representatives on the Council, this fund being for the purpose of defraying expenses of Council members when such expense is not taken care of by the organization. There was a general feeling that we should not look with favor upon this arrangement as it would have a tendency to assess twice those organizations who defray the expenses of their Council members or whose expenses are avilable from other sources. Instead, it was voted that we should urge a more free designation of alternates.

Recess—The meeting was recessed at 17h 10m to be resumed immediately following the business meeting on May 2, 1956.

A. Nelson Sayre, General Secretary
Waldo E. Smith, Executive Secretary

Second Session, May 2, 1956

The second session was called to order at 16h 46m in the Auditorium of the National Academy of Sciences—National Research Council Building, 2101 Constitution Avenue, Washington, D. C., by President Maurice Ewing.

Present—Sixteen persons were present as follows: John N. Adkins, Leroy R. Alldredge, W. W. Atwood, Jr., Lloyd V. Berkner, J. J. Capello, Frank L. Culley, Maurice Ewing, W. F. Foshag, Albert J. Hoskinson, Benjamin F. Howell, Jr., Woodrow C. Jacobs, Walter D. Lambert, Ray K. Linsley, James A. Peoples, Jr., Waldo E. Smith, and Victor Vacquier.

The President announced the total registration at the Thirty-Seventh Annual Meeting as 1348.

President Vacquier of the Section of Terrestrial Magnetism and Electricity reported that in response to a notice published in the February, 1956, issue of the *Transactions* regarding proposed name change of the Section, three choices were given and responses were very meager. At the business session of the Section on April 30, 1956, only about 35 people were present at the time that a vote was taken on the change in name, and that nine voted to change the name to the Section of Geomagnetism and Aeronomy, six voted against it, and no one voted for the present name. After some discussion he moved that the name of the Section be changed to the Section of Geomagnetism and Aeronomy which is the name adopted by the International Association. The motion carried, and the matter will subsequently be placed before the Council of the National Academy of Sciences and the membership of AGU.

The Presidents Elect of the Sections and their fellow officers were urged to proceed with the designation of committee appointments. This is especially important as we plan to issue a new directory in the late fall. The Secretaries of Sections were urged to get their minutes in promptly to meet the printer's deadline for the June issue.

Adjournment—The meeting adjourned at 16h 40m.

A. Nelson Sayre, General Secretary
Waldo E. Smith, Executive Secretary

Appendix 1—Meeting of the Council, Executive Committee, and Finance Committee of the International Union of Geodesy and Geophysics Paris, April 17–21, 1956—Summary Statement

Marking a unique occasion in the affairs of the International Union of Geodesy and Geophysics, its Council, Executive Committee, and Finance Committee convened at a time other than a scheduled General Assembly. These administrative bodies of the Union held meetings April 17–21, 1956, in Paris at the Institut d'Astrophysique. They discussed problems of the Union and reached conclusions, many of which will be circulated to the various nations for opinions and considered resolutions to be presented for official action at the next occurring General Assembly (the XIth) in Toronto in 1957. The National Academy of Sciences-National Research Council, the United States adhering body to the International Union of Geodesy and Geophysics, was represented at the meeting by J. W. Joyce.

Among the questions considered early in the sessions was that of selecting a location and date for the XIIth General Assembly of the Union. It was reported that invitations had been received from Argentina, Finland, West Germany, and India to hold the XIIth General Assembly in those countries. Various proposals were made for the dates of the XIIth and future General Assemblies, and recognition was given to the importance of holding some future meetings in areas removed from Western Europe. As a result of these discussions, the Argentinian invitation was declined and the Council will, at the Toronto Assembly, express a favorable interest in the Indian invitation.

At the conclusion of the five-day session of the Council, Executive Committee, and Finance Committee, the participants felt that this first meeting held between General Assemblies had been a profitable meeting in terms of long-range planning and discussion of administrative problems that face the Union and upon which it must take official action at the Toronto Assembly. The practice of convening the Council, Executive Committee, and Finance Committee at appropriate intervals between General Assemblies will undoubtedly continue.

A careful study of the formation of a Federation for the Permanent Services, already agreed to by URSI, IAU, ICSU, and UNESCO, and a review of its proposed Statutes and By-Laws, resulted in the Council's endorsement of the proposed Federation which will be referred to the Toronto Assembly for IUGG confirmation.

A further proposal on which the Council will recommend approval by the next General Assembly is the proposed reorganization of the International Association of Volcanology, with a change in the Association's name to the International Association of Volcanology, Composition of the Earth, and Geochronology.

Other problems discussed related to the structure of the Union, including the need for easing the duties of the General Secretary and for expanding the Bureau to provide guidance on broad policy planning for the Union. The overload in the duties of the General Secretary, brought about by the increasing activities of the Union, may be alleviated by greater cooperation of Association Bureaus and national committees, and increase in the monetary support of the office, and the transfer of some of the present functions of the office to the Federation of Permanent Services when it comes into being. The expansion of the Bureau to include the President, two Vice-Presidents, the General Secretary, the last Past President, the Chairman of the Finance Committee, and four members-at-large was agreed to on an *ad hoc* basis, any permanent change in the membership of the Bureau to require a modification of the statutes and by-laws by the General Assembly.

More basic problems of the Union were covered in

discussions relating to its future, a reexamination of its functions, and the way in which it will tie in with the International Geophysical Year.

The growth of the Union, in terms of country memberships beyond the present 48, relationships with other governmental and non-governmental international agencies, and the need for additional income, was seriously considered. Three possible suggestions were made for resolving the problem of additional monetary support: an expansion of country memberships, additional UNESCO support, and increased dues of present members.

The need for obtaining more public recognition of the Union was emphasized, and plans were laid for an expanded public relations program, including a discussion of a more effective distribution of the News Letter.

In preparation for the fullest possible collaboration in the technical planning and in the use of the data collected during the International Geophysical Year, a series of subcommittees for the various disciplines in the IGY was established to act as advisory groups to the CSAGI Reporters. These groups should provide more effective and active participation in IGY affairs than has the special IUGG Committee for the IGY, which has so far met only twice, once in Rome in 1954 and again in Brussels in 1955. It was recognized that only by current and continuing active participation in the IGY will the Union be prepared to assume its proper responsibilities when CSAGI is disbanded after the IGY ends.

As the result of a proposal made by the USSR National Committee, the Council agreed that in the future Statutes and By-Laws and resolutions of the Union will be printed in Russian, in addition to French and English texts, provided translations are supplied by the Soviet National Committee.

J. W. JOYCE

Appendix 2—Report of the Committee on Budget for the Fiscal Year Ending June 30, 1957

K. HILDING BEIJ, Chairman
ROBERT E. GEBHARDT, Acting Chairman
HERBERT N. EATON JOHN A. FLEMING
HENRY W. HEMPLE

Your Committee, on the basis of information supplied by the General and Executive Secretaries, proposes the following Budget for the fiscal year ending June 30, 1957.

Self-liquidating contracts that the Union enters into from time to time with other agencies, usually the Government, for performing work related to the interests of the Union are excluded from the Budget. Clerical assistance, miscellaneous supplies, and other related expenses are charged directly to the contract, as well as occasional work of regular employees on contracts of this type, and are excluded from the Budget.

At the present time four full-time office positions are authorized. (Formerly there were five, but letterpress composition of the *Transactions* eliminated one.) Salaries of two are set by the Executive Committee, and for this coming fiscal year include salary increases recently authorized by that Committee. The salaries of the other two positions are determined by the General Secretary within budgetary limitations. An item for $17,500 for salaries appears under General Office Expenses, and the balance for salaries is included under heading for *Transactions* as Preparation, Printing, and Mailing. It is the opinion of your Committee that the salaries of the two clerical employees should be increased during the ensuing year to the same level as set for similar work by the U. S. Civil Service Commission to allow the Executive Secretary to compete favorably on the open market.

(1) The item for Rent of office space is a new expense and is largely responsible for the deficit indicated in the proposed Budget.

(2) The anticipated net income of about $2500 from advertising in the *Transactions* was not realized last year. However, a net of $150 that was realized was about as much as was reasonably expected. The April issue of the *Transactions* carried 9⅞ pages of advertising, and if this rate can be continued during the next fiscal

Operating Statement

Estimated receipts:		
National Research Council grant		$400
Income:		
Membership dues		40,000
Transactions:		
Sales and subscriptions	$11,000	
Sales of reprints	4,500	
Gross advertising	5,000	20,500
Interest		400
Miscellaneous		300
Reserve for Directory from 1956		900
Total receipts		$62,500

Estimated expenditures:

Transactions:		
Preparation	$7,200	
Printing	21,600	
Mailing	1,000	
Editors	1,500	
Direct advertising costs	2,500	
Cost of reprints	2,200	$36,000
General office expenses:		
Rent	$3,000	
Salaries and Social Security	17,500[a]	
Retirement contribution	1,000	
Stationery and supplies	1,000	
Postage and communications	1,500	
Equipment	500	24,500
Expenses for meetings:		
Annual	$1,000	
Regional	200	1,200
Expenses, Sections		100
Expenses, Committees		200
Travel of officers		150
Miscellaneous		100
Directory (with reserve from 1956)		1,800[b]
Total expenditures		64,050
Estimated excess of expenditures over receipts (deficit)		$1,550

[a] Includes salary increases authorized by the Executive Committee.

[b] In 1954–1955 a Directory was published at a cost of $1782; $900 is carried forward from the reserve set up in 1955–1956, and an additional $900 is contemplated this fiscal year.

Statement of assets as of June 30, 1956 and 1957 (both estimated)

		1956	Changes	1957
General Funds:				
Cash Reserve		$21,632	−$980	$20,652
Reserve for Directory		900	−900	0
Permanent Fund:				
U. S. Bonds at cost[a]	$2,368			
Northwestern Federal Savings and Loan Association	9,930			
Prudential Building Association	870	13,168	+300 interest	13,468
Emergency Fund:				
Prudential Building Assn.[b]		1,000	None	1,000
T. M. and E. Award Fund:				
Liberty Building Assn.[c]		1,000	+30	1,030
Bills receivable less bills payable		3,000	None	3,000
Totals		$40,700	−$1550	$39,150

[a] Accumulated interest is now about $450.

[b] This fund is provided for emergency expenditures by the General Secretary when there is no time to secure prior approval by the Executive Committee.

[c] This fund, and anticipated future donations, will be held until the Award is established.

year a gross of $5000 or net of $3500 will be obtained. There is every reason to expect that the receipts from this source will increase rather than decrease during the next year.

(3) The sale of publications and reprints has always shown a greater income than estimated, and additional income beyond that shown in our Financial Statement is confidently expected.

Although a deficit is shown by our conservative estimates of income for the next fiscal year, the additional income outlined above will possibly offset this.

Your Committee believes that the financial status of the Union is satisfactory and that a small deficit (if it materializes) can be tolerated during the coming year.

The following recommendations are offered:

(1) Upgrade the two lower clerical positions in the office and set the salaries at the present government levels for similar work

(2) Institute a active effort to increase the membership through a membership drive during the next triennium.

Appendix 3—Report of the *Ad Hoc* Committee on Quarters for the American Geophysical Union

EARL INGERSON, Chairman
J. WALLACE JOYCE A. NELSON SAYRE
A. G. MCNISH WALDO E. SMITH

The Committee held only three meetings from January 25, 1956, to February 14, 1956, but from its appointment early in January until the final meeting its members were active in studying the problems of quarters for the A.G.U. and investigating numerous possibilities for adequate space for the Headquarters of the Union.

A tentative date of February 1, 1956, had been set for the move from quarters currently occupied in the Administration Building of the Carnegie Institution of Washingron at 1530 P St., N.W., so the first task of the Committee was to secure an agreement to let us continue in that building through June 20, 1956.

The Committee then inquired into the possibility of securing free, or low cost, space at one of the local universities. When it became evident that such space was not available a move to some university outside of Washington was considered. In the opinion of the Committee on Quarters and members of the Executive Committee consulted, such a move would not be in the best interests of the union.

At the January 25 meeting of the committee it was decided that the General Secretary should seek authorization from the Executive Committee to proceed in the securing of space in accordance with the recommendation of the *Ad Hoc* Committee. All thirty-five of the votes returned favored such authorization.

The Committee continued to look for suitable space and in the following weeks considered suites of rooms in the Dupont Circle Building, the Associations Building at 1145 19th St., N.W., The Hamilton Hotel, the new building of the American Association for the Advancements of Science on Massachusetts Avenue at Scott Circle, and in more than a dozen other office buildings of various kinds throughout the northwest section of Washington. Buildings farther out were also considered, particularly a new office building on Wisconsin Avenue near Albemarle Street, N. W., and the Chevy Chase Center at Wisconsin and Western Avenues, Chevy Chase, Maryland.

By the time of the February 14 meeting of the Committee it was evident that suitable space in an appropriate area would cost approximately $4.00 per square foot per year. At this price the most attractive space was that in the AAAS building and the committee recommended that the General Secretary negotiate for not more than 750 square feet of office space in this building.

Accordingly, on February 16, 1956, the General Secretary requested reservation of Rooms 315, 316, 317, and 318, totaling slightly over 700 square feet, in the AAAS Building for the use of the Executive Secretary of the American Geophysical Union and his staff. This space has been allotted to the Union and the tentative date for occupancy to begin is June 18, 1956, contingent upon securing proper authority of the Board of Zoning Adjustment of the District of Columbia.

The Committee requests that it be dismissed.

Appendix 4—Activities of the Cloud-Physics Committee, 1955

HELMUT WEICKMANN, Chairman
CHARLES E. ANDERSON R. R. BRAHAM, JR.
CHRISTIAN E. JUNGE

A Conference on the Physics of Cloud and Precipitation Particles was arranged by the Cloud-Physics Committee in cooperation with the Executive Secretary. Funds for the Conference were obtained through a joint Air Force–Navy contract. The Conference took place from September 7–10, 1955 at Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

More than 60 participants were invited and included only scientists and officials on American soil. The scientific program was carefully planned and limited to the subject of the Conference. It was divided into three major topics, one for each day:

(1) Condensation nuclei—condensation—droplets

(2) Ice nuclei—ice formation—ice and snow crystals

(3) Precipitation particles.

The following list of the papers presented under the

headings mentioned above gives a review of the scope of the conference:

Topic (1)

CHRISTIAN E. JUNGE: Remarks about the Size Distribution of Natural Aerosols

HORACE R. BYERS: Distribution in the Atmosphere of Certain Particles Capable of Serving as Condensation Nuclei

E. M. FOURNIER D'ALBE: Some Observations of the Geographical Distribution of Giant Hygroscopic Nuclei

UKICHIRO NAKAYA: Electron-Microscope Studies on the Nuclei of Sea Fog and Snow Crystals

VINCENT J. SCHAEFER: The Question of Meteoritic Dust in the Atmosphere

CHRISTIAN E. JUNGE: Some Facts about Meteoritic Dust

CHRISTIAN E. JUNGE: The Vertical Distribution of Aerosols over the Ocean

HELMUT WEICKMANN: Recent Measurements of the Vertical Distribution of Aitken Nuclei

RITA C. SAGALYN: Investigation of the Time Variations of Charged Nuclei in the Atmosphere

CHRISTIAN E. JUNGE: Facts and Problems of Chemical Composition of Condensation Nuclei in Unpolluted and Polluted Atmospheres

JAMES P. LODGE, JR. and BARBARA J. TUFTS: Techniques for Chemical Identification of Micron and Submicron Particles

BERNARD VONNEGUT and CHARLES MOORE: Electrostatic Method for the Measurement of Aerosols

S. J. BIRSTEIN: The Role of Adsorption in Water Condensation

CHARLES E. ANDERSON: Condensation on Natural Nuclei

L. J. BATTAN and CLAYTON H. REITAN: Dropsize Measurements in Convective Clouds

GILBERT D. KINZER and WILLIAM E. COBB: Laboratory Measurements of Growth and of the Collection Efficiency of Raindrops

RICHARD SCHOTLAND: Studies of the Flow Pattern about Large Raindrops and the Effect upon Collision Efficiency

JAMES D. WILCOX: Isokinetic Flow and Sampling

HELMUT WEICKMANN: A Nomogram for the Calculation of Collision Efficiencies

Topic (2)

J. E. MANSON: Ice and Nuclei of Ice Formation

A. RICHARD KASSANDER, LEE L. SIMS, and JAMES E. MCDONALD: Observations of Freezing Nuclei over the Southwestern United States

DAVID TURNBULL: Remarks on the Theory of Heterogeneous Nucleation of Crystals

CHARLES E. ANDERSON: Studies on Re-evaporation Ice Nuclei

C. L. HOSLER and G. R. SPALDING: The Effect of Condensation Nucleus Size and Type on the Temperature of Ice-Crystal Formation in Clouds

S. J. BIRSTEIN: Studies of the Effect of Certain Chemicals on the Inhibition of Nucleation

ROSCOE R. BRAHAM, JR., AND JOHN R. SIEVERS: Overseeding of Cumulus Clouds

HELMUT WEICKMANN: Stereoscopic Views of Snow and Ice Crystals

U. NAKAYA: Surface Structure of Ice Crystals

E. J. WORKMAN: Ice Crystal Research at New Mexico Institute of Mining and Technology

DAVID TURNBULL: Cinema on Crystal Growth

G. A. WOLFF: The Growth of Ice Crystals

J. S. MARSHALL and K. L. S. GUNN: A First Experiment on Snow Crystal Growth

U. NAKAYA: A Peculiar Phenomenon Observed in the Supercooling of Minute Droplets Suspended in the Air

D. C. BLANCHARD: The Supercooling and Freezing of Giant Waterdrops

Topic (3)

CHARLES F. BROOKS: The New International Definitions of Hydrometeors

T. W. R. EAST: Precipitation of Convective Water Clouds

WALTER HITSCHFELD: Size Distribution of Precipitation Particles

A. H. WOODCOCK: Atmospheric Salt in Nuclei and in Raindrops

D. C. BLANCHARD: Discussion of Raindrop Distributions Determined during Project Shower, Hawaii, 1954

HELMUT WEICKMANN: The Snow Crystal as Aerological Sonde

PAULINE M. AUSTIN and RAYMOND WEXLER: Analysis of Space and Time Variations in the Radar Echo Intensity of Showers

R. H. DOUGLAS and M. P. LANGLEBEN: Snow Growth and Aggregation in Generating Cells

R. M. CUNNINGHAM: A Discussion of Generating-Cell Observations with Respect to the Natural Existence of Freezing or Sublimation Nuclei

DAVID ATLAS: Radar Measurements of Precipitation Growth

RAYMOND WEXLER: The Melting Layer

At the conference the Executive Secretary indicated the possibility that the proceedings of this Conference would be published as a first volume of the new monograph series of the AGU. Recently, however, difficulties have been encountered in obtaining funds for such publication. As it stands now, the proceedings most probably will be printed as an Air Force Geophysical Research Paper. This solution, of course, is undesirable because of several reasons: (1) Air Force reports have limited circulation, (2) reprints for authors are usually not available, (3) a number of authors have indicated that they would prefer to publish in a scientific journal.

It appears that a matter of principle is here involved: the authors were asked to present latest results of their research and they did this. This made the discussions most stimulating and it was the consensus of opinion of all participants that the Conference was excellent and a full success. The level of future Conferences could be kept on such a high standard if the authors could be assured proper publication of their efforts. The problem of the publication of such proceedings should therefore be given serious consideration.

The editing of the papers and the discussions is almost completed.

Appendix 5—Report of the American Geological Institute's Board of Directors Meeting, Chicago, Illinois, April 26, 1956

Attending for the American Geophysical Union were Director E. A. Eckhardt and George E. Manger, alternate for Director H. R. Joesting.

The following report is made by the senior representation of the AGU on the AGI Board of Directors. Since AGU will receive a copy of the minutes of this meeting at a later date no attempt will be made to detail the business transacted at the meeting. All but one of the member societies was represented at the meeting and the entire group of directors took an active and constructive part in the proceedings.

The Executive Committee reported that the present method by which the member societies support AGI by contributions from their treasuries with pertinent decisions by their governing boards necessary from year to year is considered by it to be neither suitable nor adequate. After considerable discussion the following statement of facts was endorsed by the Board.

"The Executive Committee of AGI recommends to its Board of Directors that it adopt the following statement and recommendations to be transmitted to the member societies of the Institute.

"The Board of Directors of AGI believes that the Board has performed faithfully and well its functions in providing for the cooperative efforts of the member societies and in providing a well-received forum for the discussion of problems common to the profession. Though far from having realized its full potential it is believed that substantial progress has been and is being made by the Institute. The Board believes that the present form of organization as a federation of essentially all geological societies of the United States should be preserved.

"The operating experience of the Institute over a period of eight years has demonstrated that the method of financing used so far is unsuitable and inadequate. The financial support by the member societies is only in exceptional cases broadly related to their numerical strength, whereas in the circulation of the Newsletter and some other respects the costs of AGI are dependent upon the number of individual members. During recent years the member society contributions have been maintained at a substantially constant level. They have been somewhat irregular as to timing and dependent upon year to year action by the respective governing boards.

"One basic element in the Institute is its Executive Director, his office staff, his office space and facilities, and his travel expenses to Board meetings. This provides only for an organization in being without performing any functions which involve spending additional money. On an austerity basis this element would cost at least $20,000 per annum. A more reasonable figure is $25,000.

"A second basic element of the Institute is its means of communication, the Newsletter. Allowing for circulation growth its cost, less advertising income, should level off between $15,000 and $20,000.

"These basic costs may therefore be expected to total between $40,000 and $45,000, depending largely on the Newsletter volume.

"Additional funds for the important projects for which AGI really exists, such as stimulating interest in the geological sciences in the high schools and in the minds of the general public, service duties to geologists like publishing directories, glossaries, military deferment policies and practices, and other governmental and foreign relations of individual geologists and societies, service to geologists seeking employment or employees, these funds must and will come from contributions from industrial associates and individuals, grants from foundations, advertising and from special grants from member societies. The Board of Directors of AGI through its officers and finance committee will be responsible for seeking such funds and such projects will be undertaken only to the extent that such funds are received.

"The Board of Directors believes that the cost of the basic elements above described should be the direct responsibility of the member societies. The basic income of AGI should be just as dependable and predictable as the dues income of the member societies and should grow in proportion to the increase in their numbers."

The recommendations based on these facts which had been prepared by the Finance Committee and approved by the Executive were not approved by the Directors and they were referred back to the Finance Committee for reconsideration in the light of the discussion which was participated in by nearly all present.

The meeting reflected a feeling that maintaining an Executive Director, providing him assistants, office space, and facilities which constitute an operating organization is the responsibility of the member societies which should provide the funds required for it. It seems to be the feeling that within a year or two the Newsletter circulation should be restricted to paid subscribers. The money required for special projects should come from outside sources such as industrial associates, foundations, individuals and perhaps sometimes from one or more member societies.

The AGU is one of a small minority of member societies which have never made even a token contribution to AGI. While this is not a matter of immediate urgency your representative recommends that AGU determine how many of its members qualify for representation by AGI and how many of these may also be members of other member societies which are actively supporting AGI, how many of them desire to be so represented to the extent of paying $2.50 per member, which is the average cost per member of having the Institute in being and of publishing and distributing the Newsletter. This does not include any cost for any of the projects which AGI undertakes. The time may come when those participating in AGI will have to pay their pro rata share of the cost. A long-range review by AGU of its position would be constructive.

E. A. ECKHARDT

Report on First Mid-Pacific Regional Meeting

This meeting was held jointly with the 141st National Meeting of the American Meteorological Society, sponsored by the Geophysical Society of Hawaii. It was held in Honolulu, Hawaii, November 15–18, 1955. A total of 103 delegates were registered: 75 papers were given during the three days; seven were read by title only. Of the 75 papers, ten were given in a symposium on weather reconnaissance during the International Geophysical Year with Thomas S. Moorman, Jr., Brigadier General USAF, as chairman.

Following registration during the morning of November 15, the meetings were officially convened during a luncheon at the Reef Hotel, the meeting headquarters. Alan H. Shapley of the Central Radio Propagation Laboratory, National Bureau of Standards, and Vice Chairman of the U. S. National Committee for the IGY, discussed the IGY program in the Pacific area. Formal sessions were held in fields of research such as meteorology of the jet stream, cloud physics, oceanography, tropical meteorology, synoptic meteorology, etc. Field trips were held to points of geophysical interest, including the volcano on the Island of Hawaii, and various laboratories in the Islands that are active in geophysical research.

THOMAS S. AUSTIN
Secretary-Treasurer
Geophysical Society of Hawaii

Annual Report of the Pacific Northwest Regional Committee

The highlight of our year was, of course, the Annual Fall Meeting held in Portland on November 17–18, 1955, previously reported. Activities prior to that date were largely in preparation for the meeting, and in the months since a number of plans have been made for 1956 meeting. A Program Committee appointed by Chairman Sachs and headed by R. T. Beaumont has been at work since February, 1956 and an Arrangements Committee was appointed in May, 1956.

The following Regional Committee members were elected in April to serve for the 1956–1959 triennium: Franklin I. Badgley, Clifford A. Barnes, Norbert H. Leupold, Fred Natella, Milton S. Sachs, Vail P. Schermerhorn, and Wilbur D. Simons.

A meeting of the new Regional Committee was held in Seattle on June 12 during the sessions of AAAS at which time Barnes and Badgely were elected Chairman and Secretary-Treasurer, respectively, for the year beginning July 1, 1956. The Program, Arrangements, and Regional Committees then met jointly and selected November 8 and 9, 1956 and Seattle, Washington as the time and place of the next annual meeting.

The Regional organization enters its third year with a balance of $113.96 in its treasury.

VAIL P. SCHERMERHORN
Secretary-Treasurer

Additions to the Membership

January 11 to July 10, 1956

ABRAHAMS, MR. JOHN HENRY, JR., 2732 Kentucky St., N.E., Albuquerque, N. Mex. (*fg*)

ABRAMS, MR. WILLIAM J., 434 N. Plankinton St., Milwaukee, Wis. (*g*)

ALVERSON, MR. JAMES E., 2533 W. 155th St., Gardena, Calif. (*eg*)

ANDERS, MR. ROBERT BERNARD, 1500 Dexter St., Austin 4, Texas (*cefg*)

AULT, MR. WAYNE U., Lamont Geological Observatory, Palisades, N. Y. (*f*)

BAGLEY, MR. CHARLES S., 1314 Ohio Ave., Alamogordo, N. Mex. (*a*)

BALAK, MR. ABRAHAM HARRY, 5016 Deal Dr., Washington 21, D. C. (*a*)

BALCH, MR. WILLIAM T., P.O. Box 380, Bakersfield, Calif. (*eg*)

BARNES, MR. STANLEY M., 7402 Via Rio Nido, Downey, Calif. (*g*)

BARON, MR. ROBERT JACOB, 3310 W. Coqueling Ter., Chevy Chase 15, Md. (*e*)

BARRY, MISS FRANCES H., 2231 California St., N.W., Washington 8, D. C. (*a*)

BARTHOLOMEW, MR. WILLIAM STANLEY, 640 Winding Way, Salem, Ore. (*g*)

BEATTY, MR. MATTHEW E., National Park Service, 900 N. Lombardy St., Richmond 20, Va. (*g*)

BELL, MR. BASIL E., P. O. Box 4849, Ngong, Kenya (*eg*)

BERNDT, MR. HERBERT W., P.O. Box 478, Woodland Park, Colo. (*eg*)

BITTING, MR. HARRY G., 7018 Freeport St., Hyattsville, Md. (*a*)

BLAKE, MR. WESTON, JR., 147-A Newton St., Weston 93, Mass. (*cefgh*)

BLAKELY, MR. WILLIAM EARL, Triad Oil Co., Ltd., 505 8th Ave., W., Calgary, Alta., Canada (*abh*)

BLANK, MR. HORACE RICHARD, JR., Geology Dept., University of Washington, Seattle 5, Wash. (*dgh*)

BLOOMER, MR. HAROLD W., 3153rd Instal. Sqd., Box 2, APO 30, New York, N. Y. (*d*)

BLUNT, MR. DUANE E., East 3rd and Anderson, Ellensburg, Wash. (*g*)

BLUST, MR. FRANK A., 630 Federal Bldg., Detroit, Mich. (*g*)

BORGMAN, MR. LEON EMRY, 5701 Carew St., Bellaire, Texas (*e*)

BOWER, MR. EVAN G., 1295 E. Orchid Drive, San Bernadino, Calif. (*eg*)

BOYD, MR. LEONARD G., 335 N. Citrus Ave., Vista, Calif. (*bceg*)

BRADFORD, MR. JUSTIN T., Rt. 2, Granby, Mo. (*bd*)

BRADLEY, MR. JAMES JEAN, Colorado School of Mines, Business Office Box 60, Golden, Colo. (*b*)

BRADLEY, MR. JOSEPH N., 2412 19th St., N.W., Washington 9, D. C. (*cg*)

BRAKENSIEK, DR. DONALD L., ARS, Ind. Res. Bldg., Colorado A & M College, Fort Collins, Colo. (*g*)

BRAUGHT, MR. GENE, Rm. R-203, Inst. of Technology, 3621 Olive St., St. Louis 8, Mo. (*b*)

BRIDGE, MR. THOMAS E., Geology Dept., Colorado A and M College, Fort Collins, Colo. (*dfh*)

BROCK, DR. BYRON BRITTON, P.O. Box 4587, Johannesburg, South Africa (*bdefh*)

BROGGI Y MOREL, DR. JORGE A., Apartado 2559, Lima, Peru (*abcdefgh*)

BROWNE, MISS IRENE M., 183 Calumet St., Roxbury, Mass. (*ce*)

BUCKNELL, MR. ROBERT I., 910 13th St., Golden, Colo. (*abd*)

BUCKWOLD, DR. S. JOSHUA, New Mexico Institute of Mining and Technology Campus Station, Socorro, N. Mex. (*fg*)

BUESCHER, MR. J. E., Vector Manufacturing Co., P.O. Box 18212, Houston 23, Texas, (Corp. Mem. representative)

BULLARD, SIR EDWARD CRISP, Madingley Rise, Madingley Road, Cambridge, England (*abdefh*)

BURGERS, PROF. JOHANNES M., 4622 Knox Road, Apt. 7, College Park, Md. (*befh*)

BURKHART, MR. MARVIN DERRIL, P.O. Box 540x, Route 2, Clinton, Md. (*ce*)

CHAMBERLAIN, DR. ADRIAN RAMOND, Colo. A. and M. College, Ft. Collins, Colo. (*cg*)

CHANG, MR. FENG-KENG, 51 Vandeventer Pl., St. Louis 8, Mo.

CHAPMAN, DR. SEVILLE, 2343 Kensington Ave., Buffalo, N. Y. (*cd*)

CHUN, MR. ROBERT Y. D., 1517 5th Ave., Los Angeles, Calif. (*ceg*)

CLARK, PROF. GEORGE BROMLEY, Dept. of Mining Engineering, Missouri School of Mines, Rolla, Mo. (*b*)

COCHRANE, MR. NOEL J., "Tregenna," 138 Tinsley Lane, Three Bridges, Sussex, England, (*bcefgh*)

COLVIN, CAPT. MARC JAY, JR., 747 W. Canterbury Rd., St. Louis, Mo. (*b*)

CONNOR, CAPT. JAMES J., JR., 4233 Snow St., St. Louis 20, Mo. (*b*)

COREY, MR. GILBERT L., S.C.I.A., American Consulate, Guayaquil, Ecuador (*cg*)

CROMWELL, MR. TOWNSEND, 2621 Inyaha Lane, La Jolla, Calif. (*e*)

DAWDY, MR. DAVID RUSSELL, 1713 Addison St., Berkeley, Calif. (*g*)

DEAN, MR. LAWRENCE ALLEN, 5418 N.E. Davis, Portland, Ore. (*cg*)

DEANE, MR. ROY ERIC, 276 Lawrence Ave., E., Toronto 12, Ontario, Canada (*efh*)

DEFFEYES, MR. KENNETH S., Geology Dept., Guyot Hall, Princeton University, Princeton, N. J.

DE OLIVEIRA MOTTA, SR. SERTORIO, Caixa Postal 199, Natal, R.G. Do Norte, Brasil (*b*)

DICK, MR. SHELDON, 43 Branch Ave., Freeport, N. Y. (*befh*)

DOUTHIT, CAPT. THOMAS D. NATHAN, 662 Rochester Dr., St. Louis, Mo. (*bd*)

DOWNS, MR. JAMES P., Apt. 23, 251 10th St., Atlanta 13, Ga. (*bd*)

DUQUET, MR. ROBERT THEODORE, Apt. 1A, 73 W. 174 St., Bronx 53, N. Y. (*ceg*)

DURHAM, MR. DAVID LEON, P.O. Box 895, Whittier, Calif. (*h*)

ECKHOFF, MR. OSCAR BRADLEY, P.O. Box 119, Chester, S. C. (*bh*)

EDWARDS, MR. CHARLES GORHAM, 2 Vichy Road, Rolla, Mo. (*begh*)

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FARR, MR. JOHN BRENT, P.O. Box 7128, New Orleans, La. (*b*)

FEDUKOWICZ, DR. WACLAW, 85–24 110th St., Richmond Hill 18, N. Y. (*e*)

FORD, MR. EDWIN FOSTER, 3071 S. Woodrow St., Arlington, Va., (*cg*)

FREEMAN, MR. CHARLES V. AESB-Area III, APO 28A, New York, N. Y. (*bdfgh*)

FRIEND, MR. FRED F., 5527 Fernwood Ave., Los Angeles 28, Calif. (*g*)

FUQUA, MR. WALLACE DUNHAM, 1400 El Nido Way, Sacramento, Calif. (*bg*)

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GAUL, MR. ROY DAVID, P.O. Box 5025, College Station, Texas (*ce*)

GOLDBERG, DR. PHILIP A., Dept. of Physics, University of Oregon, Eugene, Ore. (*d*)

GUINN, MR. PAUL R., U. S. Atomic Energy Commission, Operations Office, Grand Junction, Colo. (*bcdgh*)

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HENDRICKS, MR. DAVID WARREN, 696–8th Ave., San Francisco, Calif. (*g*)

HESS, MR. GEORGE BURNS, 150 Fitz Randolph Road, Princeton, N. J. (*abcdeh*)

HIRSHMAN, MR. JULIUS, Lamont Geological Observatory, Palisades, N. Y. (*abde*)

HOFFMAN, LT. RENNER B., 1947 S. Broadway, Wichita, Kansas (*bdh*)

HUANG, MR. CHING-WAI, Apt. 1, 604 Francis St., Houston 6, Texas (*g*)

HUNKINS, MR. KENNETH LELAND, School of Mineral Sciences, Stanford, Calif. (*bdh*)

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JENKINS, MR. JULES E., 7665 Sheridan Road, Chicago, Illinois (*b*)

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KALKANIS, MR. GEORGE, 1503 Francisco St., Berkeley 3, Calif. (*ceg*)

KALLMANN, DR. HILDEGARD KORF, 2239 Midvale Ave., Los Angeles 64, Calif. (*cd*)

KANCHANALAK, MR. BOONCHOB, The Thai Royal Irrig. Dept., Bangkok, Thailand (*cg*)

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Transferred from inactive status to active status January 11 to July 10, 1956

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Special Announcements

NEW ADDRESS FOR AGU—Please note that the address of AGU is now 1515 Massachusetts Avenue, N. W., Washington 5, D. C. This is the new building of the American Association for the Advancement of Science. The AGU occupies Rooms 315 to 319.

CHANGE IN DATES OF OUR ANNUAL MEETING FROM APRIL 27 TO MAY 1, 1957—As announced in the June issue of *Transactions*, the Annual Meeting was to be held May 6 to 8, 1957 but to follow the custom of holding our meeting in the week immediately following the meeting of the National Academy of Sciences, the meeting has been moved forward one week from April 29 to May 1, Monday to Wednesday. This is the first call for titles and abstracts of papers and for suggestions for symposia and other matters relating to the meeting. Send communications to the office of AGU at its new address (1515 Massachusetts Avenue, N. W., Washington 5, D. C.) or to the appropriate Section Secretary (see new officers published in the June issue, p. 384).

MEETING OF THE PACIFIC NORTHWEST REGION IN SEATTLE, WASHINGTON, NOVEMBER 8-9, 1956—The Regional Committee for the Pacific Northwest has set Seattle, Washington, as the place and November 8-9 as dates for the meeting this coming fall. The Program Committee is at work and is headed by R. T. Beaumont, 209 S. W. 5th Avenue, Ross Building, Portland 4,

Oregon. Information concerning the meeting can be secured from Mr. Beaumont or from Secretary-Treasurer Vail P. Schermerhorn (230 Custom House, Portland, Oregon).

MEETING OF THE PACIFIC SOUTHWEST REGION TO BE HELD AT SACRAMENTO, CALIFORNIA, FEBRUARY 14–16, 1957—The Pacific Southwest Regional Committee has set their annual meeting to be held in Sacramento, February 14–16, 1957. Harlowe M. Stafford (U. S. Geological Survey, 2520 Marconi Avenue, Sacramento, California) is General Chairman for the Meeting and Harvey O. Banks (431 Ross Way, Sacramento, California) is Chairman of the Program Committee. Interested persons should write to one of these or to officers or members of the Regional Committee.

ELEVENTH GENERAL ASSEMBLY OF IUGG—As noted in the June issue, the General Assembly will be held in Toronto, Canada, September 3 to 14, 1957. Word from the various Associations indicates that plans are developing rapidly to make this meeting very successful. Any who desire to take part in this meeting should advise the office of AGU or the appropriate Section Secretary of your plans or in case you are in direct touch with the International Bureau of a particular Association, please send the office of AGU a carbon of your correspondence in order that we may be informed of developments.

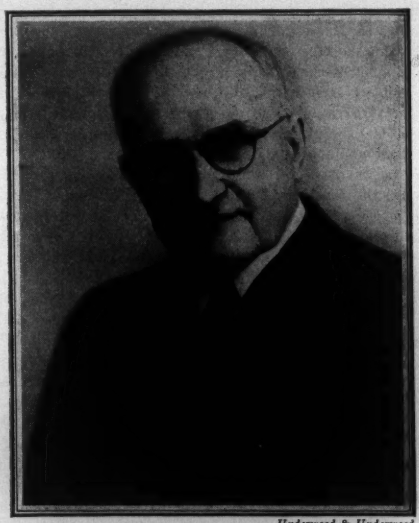
PUBLICATIONS OF IUGG AND ITS ASSOCIATIONS AVAILABLE—Attention is called to the advertisement in the advertising section of this issue to the fact that certain international publications are available in the office of AGU. These are in general available for the cost of mailing and handling. The schedule of costs has been set up as shown in the ad. Particular attention is called to the many items of *Bibliography of Hydrology* available.

Transactions
American Geophysical Union

VOLUME 37 OCTOBER 1956 NUMBER 5

John Adam Fleming

A warm friend to very many and a distinguished scientist passed away quietly in San Mateo, California, July 29, 1956, while visiting with his only child, Mrs. Margaret F. Atkinson. He was 79 years old. He had recently taken up residence in a nursing home near by, where he lived an interested and pleasant existence for a few weeks. From December, 1955, until June, 1956, he had lived at the Cosmos Club in Washington in the company of old friends. His wife had passed away in November, 1955.



Underwood & Underwood

JOHN ADAM FLEMING
General Secretary, 1925–1947
Honorary President, 1947–1956

John Adam Fleming was born in Cincinnati, Ohio, on January 28, 1877, the son of Americus V. and Catherine B. Fleming. He graduated as a civil engineer at the University of Cincinnati in 1899 (DSc in 1933). For some time, he was a building contractor with his brother. After meeting Dr. Louis A. Bauer, Dr. Fleming joined him as an aide in terrestrial magnetism at the U. S. Coast and Geodetic Survey in Washington from 1899 to 1903. When Dr. Bauer, with the help of Andrew Carnegie, founded the Department of Terrestrial Magnetism, in Washington, Fleming became Chief Magnetician, a post he held from 1904 till his re-

tirement in 1946, serving as Director from 1943 to 1946. From 1930 to 1934 he was Acting Director. He was thus associated with this Department of the Carnegie Institution of Washington for 42 years, an institution which he served with an intense and devoted enthusiasm.

Dr. Fleming was a man of enormous energy with a most notable capacity for getting things done. His work was his life and his hobby, but above all he enjoyed companionship and discussions with his many friends and colleagues.

As a Director, he possessed several unusual gifts. He made each staff member who brought in a scientific paper feel that his work, however small, was appreciated, provided it had resulted from studious and persistent effort. When a man made a discovery, Fleming would praise him, but usually warn him not to overestimate the importance of the effort. In this simple and effective way he was able, on behalf of the Carnegie Institution, to encourage his workers, whether they were in difficulty or getting along very well. He was highly demanding, some thought almost unreasonably so, in insisting that all work must be clearly written up and presented, with all necessary hyphens in place, and with neatly arranged headings for tables and titles for figures. He won all the battles with his staff about format and presentation of scientific material. Since he was Assistant Editor and subsequently Editor of the *Journal of Terrestrial Magnetism and Atmospheric Electricity* from 1899 to 1948 and Editor of the *Transactions* of the American Geophysical Union until 1947, he probably won almost all similar battles with scientists the world over, whose work he had the pleasure of editing.

Dr. Fleming has often been credited with possessing a most unusual gift for judging the future possibilities and capabilities of the young men he brought to DTM. This has been shown, not only by the work at DTM, but by their outstanding contributions in positions of great trust elsewhere, after leaving or on leave from the Carnegie Institution. Among these, to name only a few, were men like Berkner, Breit, Hafstad, Johnson, McNish, Sherman, and Tuve—now Director of the DTM. A large number of young men, who later became highly distinguished in science, were also at one time visiting investigators at DTM.

Dr. Fleming took a major part in organizing and planning the magnetic and electric surveys of the Earth since 1900. In the early years of this century there were few magnetic measurements on land, and the oceans were largely an open gap, in so far as man's description of this aspect of his environment was concerned. The existing standards for the accuracy and intercomparability of observations were defective. It was largely through the driving force, initiative, and capacity of Fleming that so many of these deficiencies were removed. He designed and constructed new and improved instruments for use on land and especially at sea. Under his direction, over 50 major land magnetic-survey expeditions to all continents and three cruises of the *Galilee* and seven of the nonmagnetic ship *Carnegie* took place with immense practical as well as scientific benefits to mankind. His men participated in various polar expeditions of others, even to the extent of travel by Zeppelin and submarine. He also directed what was probable then the most extensive program in physical and biological oceanography during the first quarter of the present century, especially in connection with the cruises of the *Carnegie*. Among a few of the major contributions were the greatly improved description of the geomagnetic field, the first isomagnetic world charts designating the major patterns of magnetic secular change, and the variation of atmospheric electricity according to universal time.

Under Fleming, the DTM's observatory program in geomagnetism, earth currents, ionosphere, cosmic rays, meteorology, atmospheric electricity, and solar physics were initiated and essentially completed. These programs resulted in noteworthy contributions to solar and terrestrial physics. Important pioneering laboratory programs were created in nuclear physics and biophysics. In all of these Fleming contributed his help and enthusiasm, though he did not participate much directly in the associated research activities.

During two World Wars he served his country well. He had a part in the development of the magnetic mine by DTM during World War I and submarine detection. In World War II he also organized major efforts, and his Department contributed in the development of proximity fuses, and did useful work in magnetic, radio, and biological problems.

Another major and almost personal accomplishment of Fleming was in connection with the growth of the American Geophysical Union. In 1920, a year after the organization of AGU, he became Secretary of the Section of Terrestrial Magnetism

and Electricity, continuing until 1929. From 1925 to 1947 he was General Secretary of the Union. It was during these years and under his inspiration, in large measure, that the Union had its greatest growth, successfully initiating a number of outstanding research projects in geophysics which have since become commonplace (see Origin and Development of AGU by Dr. Fleming, Trans., v. 35, pp. 1–46, 1934). His great contributions to the development of AGU were recognized in his election as Honorary President for life in 1947. During his 22 years as General Secretary, over 13,000 pages were published in the *Transactions*, the editorship of which was almost solely his. He devoted his weekends, holidays, and evenings unselfishly to this work.

Fleming served also on many other learned societies, too numerous to mention. He was a member of the National Academy of Sciences and Chairman of its Section of Geophysics, which he was instrumental in organizing. He was a fellow or member of the Washington Academy of Sciences, American Physical Society, American Geographical Society, and American Institute of Mining and Metallurgical Engineers. He also belonged to the Seismological Society of America, the Philosophical Society of Washington (President, 1925), National Institute of Social Sciences, Sigma Xi, State Russian Geographical Society, Royal Society of New Zealand, Michelsen Institute, Geophysical Society of Finland, Norwegian Academy of Sciences, and Geological Society of Peru. He was President of the International Association of Terrestrial Magnetism and Electricity from 1930 to 1948 and of the International Council of Scientific Unions from 1946 to 1949.

He was the recipient of various medals and prizes, in addition to the William Bowie Medal of AGU in 1941 (for unselfish cooperation in geophysical research). He was awarded the Charles Chree Medal and Prize of the Physical Society (London) in 1945.

He leaves a daughter, Mrs. Margaret F. Atkinson, in San Mateo, California, and a brother, Oliver P. Fleming, in Nashville, Tennessee. Dr. Fleming will be warmly remembered by all those who knew him.

E. H. VESTINE

A New Determination of the Figure of the Earth from Arcs

BERNARD CHOVITZ AND IRENE FISCHER

Abstract—As part of a broader study on the figure of the Earth, a tentative size is derived, based on four arcs: a meridional arc extending from South Africa to Scandinavia, a meridional arc extending from Chile to Canada, a parallel traversing the United States, and a parallel extending from western Europe to Siberia. The first two arcs were completed within the past three years and are the longest of their kind ever available—about 100° in length. The information they supply on the Earth's size is presented here for the first time.

The data were applied in two forms: astrogeodetic (free-air), and isostatically reduced deflections. The solutions assumed a flattening, $f = 1/(297 \pm 1)$. The following values were obtained for the semi-major axis a: free-air, 6,378,240 ± 100 m; and isostatic, 6,378,285 ± 100 m. As a single value, 6,378,260 ± 100 m can be taken. The uncertainty of a is due not only to the data, but also in large measure to the assumed uncertainty in f, and to an uncertainty due to the systematic undulations of the geoid as given by Jeffreys.

Up to the present no determination of the figure of the Earth, except the Krasovskiy solution [*Zverev*, 1950] has employed an individual connected arc longer than 50° in length. *Jeffreys* [1948] in his recent solution based on arc measurements used no arc longer than 38° in length, and in particular, no meridional arc longer than 27°.

Since 1953, however, two important pieces of geodetic work have been completed. In 1954 the last unsurveyed section of the long anticipated arc of the 30th meridian extending from Scandinavia to South Africa was finished by a field party from the Army Map Service; a Hiran connection by the U. S. Air Force from Crete to Egypt and an alternate connection through the Middle East joined the African portion of the arc to the European portion. In the Western Hemisphere, the Inter-American Geodetic Survey completed its field work in Central and South America in 1953 on an arc extending from the southern border of the United States to southern Chile. The material of these two long arcs is applied here in a solution for the figure of the Earth for the first time.

The investigation presented here is preliminary in the sense that it is a part of a much broader study on the figure of the Earth, which will employ entire geodetic networks rather than only arcs. It is felt, however, that it would be of general interest to present a tentative solution based on the above arcs, because of their unique features, namely, their extraordinary length and their extension into the Southern Hemisphere.

At this point it might be appropriate to mention that the conception and execution of the entire project are due largely to F. W. Hough, under whose general direction this particular investigation was carried out. The most crucial piece of information, the missing link in the arc of the 30th meridian, was carried out under the direction of D. L. Mills.

Data—Figure 1 shows the general size and location of the arcs employed. Data on their lengths and positions are given in Table 1. Not all of the stations available along the arcs were used; some selection was made in order to give a fairly uniform spacing between the points along the arcs. In general, the distance between two consecutive points was about 1°, and, with a very few exceptions, always less than 3°. The geodetic and astronomic values were, with few exceptions, of first-order quality.

In the Western Hemisphere all of the Latin American data were adjusted to North American 1927 Datum (Clarke 1866 ellipsoid). In the Eastern Hemisphere, all of the non-European material was adjusted to European Datum (Hayford ellipsoid). The adjustments were computed by the variation of coordinates method piecewise on each section of arc between base and azimuth controls. The root-mean-square direction errors for each section were well within the criteria demanded for first-order work.

Two types of deflection data were employed in the solutions. In the first type, the difference between the observed astronomic value and the adjusted geodetic value of the station, the so-called 'free-air' deflection, was taken unchanged. In the second type, the calculated effect of the topography surrounding the station, reduced in accordance with the theory of isostasy, was subtracted from the free-air deflection, this corrected quantity being called the 'isostatic' deflection. The corrections were obtained on the basis of the Pratt-Hayford isostatic theory with depth of compensation at 113.7 km. For comparison, depths of compensation

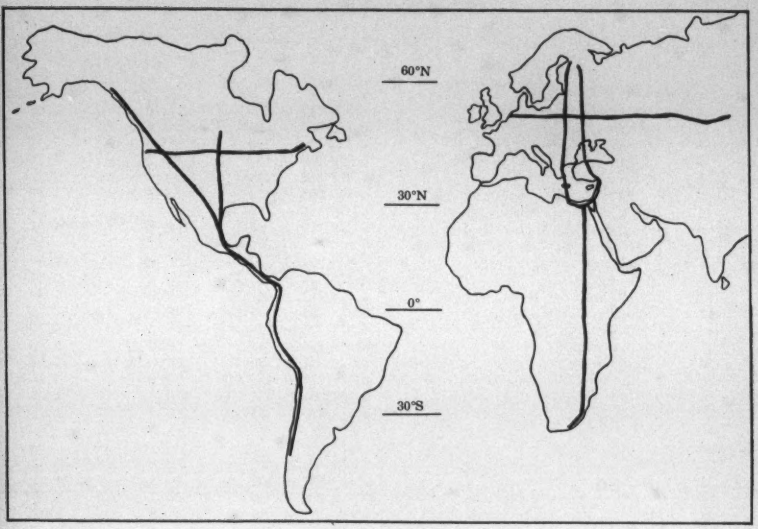


FIG. 1 – The arcs

TABLE 1 – *The arcs*

Designation	From $\begin{cases}\varphi\\ \lambda\end{cases}$	To $\begin{cases}\varphi\\ \lambda\end{cases}$	No. of points	Length	Length
	° ′ ″	° ′ ″		°	km
Pacific meridian	41 08 09 S 73 02 56 W	58 58 16 N 135 13 09 W	88	100[a]	11,000
98° meridian	41 08 09 S 73 02 56 W	49 08 01 N 96 32 17 W	75	90	9,900
24° meridian	33 59 25 S 25 30 46 E	65 00 57 N 25 30 E	71	99	10,900
32° meridian	33 59 25 S 25 30 46 E	64 03 24 N 28 50 01 E	86	98	10,700
44° parallel	45 11 05 N 67 16 53 W	44 03 29 N 123 05 27 W	25	40	4,400
52° parallel	52 09 20 N 4 29 02 E	52 10 20 N 82 29 33 E	41	48	5,300
	52 09 20 N 4 29 02 E	51 21 20 N[b] 58 32 06 E	27	33	3,700

[a] Meridional component.
[b] Isostatically reduced portion.

of 96 km and 120 km were considered also but, the difference between these and 113.7 km proved negligible compared to other sources of error. The computation of the isostatic deflections was carried out in a manner similar to that used by *Hayford* [1909, 1910], but a few changes worth mentioning were made:

(1) The sectors of the template were made

TABLE 2 – *Results of thirty-six solutions*

Solution	Location	a	$1/f$	σ
		m		"
Free air				
1	Pacific meridian	6,378,813 ± 306	291.6 ± 2.7	7.86
2	98th meridian	6,378,881 ± 583	290.9 ± 4.7	7.95
3	Pacific meridian & 44th parallel	6,378,356 ± 150	295.6 ± 1.4	7.33
4	98th meridian & 44th parallel	6,378,238 ± 168	296.2 ± 1.4	7.26
5	24th meridian	6,377,850 ± 178	301.3 ± 1.8	5.67
6	32nd meridian	6,378,004 ± 153	299.8 ± 1.5	5.41
7	24th meridian & 52nd parallel	6,378,166 ± 70	298.2 ± 0.7	5.20
8	32nd meridian & 52nd parallel	6,378,189 ± 66	298.1 ± 0.7	5.02
9	Pacific meridian	6,378,214 ± 52(84)	297.0	7.99
10	98th meridian	6,378,148 ± 61(97)	297.0	7.99
11	Pacific meridian & 44th parallel	6,378,212 ± 47(78)	297.0	7.33
12	98th meridian & 44th parallel	6,378,150 ± 53(89)	297.0	7.23
P1	44th parallel	6,378,175 ± 134(242)	297.0	4.25
13	24th meridian	6,378,276 ± 41(79)	297.0	5.87
14	32nd meridian	6,378,291 ± 36(77)	297.0	5.50
15	24th meridian & 52nd parallel	6,378,270 ± 35(71)	297.0	5.25
16	32nd meridian & 52nd parallel	6,378,284 ± 32(70)	297.0	5.05
P2	52nd parallel	6,378,212 ± 83(182)	297.0	3.97
Isostatic				
17	Pacific meridian	6,378,408 ± 170	295.6 ± 1.5	4.37
18	98th meridian	6,378,508 ± 302	294.5 ± 2.5	4.12
19	Pacific meridian & 44th parallel	6,378,326 ± 86	296.3 ± 0.8	4.22
20	98th meridian & 44th parallel	6,378,309 ± 93	296.2 ± 0.8	4.00
21	24th meridian	6,377,665 ± 141	303.8 ± 1.4	4.47
22	32nd meridian	6,377,825 ± 109	302.3 ± 1.1	3.85
23	24th meridian & 52nd parallel	6,377,994 ± 83	300.5 ± 0.8	4.34
24	32nd meridian & 52nd parallel	6,378,036 ± 69	300.2 ± 0.7	3.79
25	Pacific meridian	6,378,253 ± 28	297.0	4.37
26	98th meridian	6,378,214 ± 31	297.0	4.12
27	Pacific meridian & 44th parallel	6,378,255 ± 27	297.0	4.21
28	98th meridian & 44th parallel	6,378,219 ± 30	297.0	4.00
P3	44th parallel	6,378,309 ± 116	297.0	3.67
29	24th meridian	6,378,335 ± 36	297.0	5.16
30	32nd meridian	6,378,353 ± 29	297.0	4.36
31	24th meridian & 52nd parallel	6,378,326 ± 32	297.0	4.72
32	32nd meridian & 52nd parallel	6,378,344 ± 27	297.0	4.14
P4	52nd parallel	6,378,108 ± 105	297.0	3.10

equiangular in order to facilitate map reading. (This was suggested by D. A. Rice of the U. S. Coast and Geodetic Survey and has been practiced there for some time.)

(2) The map reader's job was limited solely to the reading of the topography, no computations being required of him.

(3) All computations were performed on electronic computing machinery, the Army Map Service UNIVAC.

(4) Use was made of the theory and tables of *Lambert* and *Darling* [1938; *Darling*, 1949] which corrected and improved Hayford's theory.

(5) The topographic influence around a station was considered only up to a radius of 470 km. The area beyond was neglected since it can be shown that its influence (isostatically reduced) never amounts to more than 0.3 seconds of arc [for an example, see *Fischer*, 1954].

At the time the solutions presented here were worked out, isostatic deflections were not available for the portion of the 52nd parallel east of 58° 32′ E. This is indicated in Table 1.

Individual solutions—By the arc method, given n points along an arc with the corresponding deflections, a set of n observation equations can be set up with the change in the semi-major axis Δa, the change in the square of the eccentricity Δe^2, and the initial orientation of the arc ξ_1 or η_1 as the unknowns. If the arc is a parallel, however,

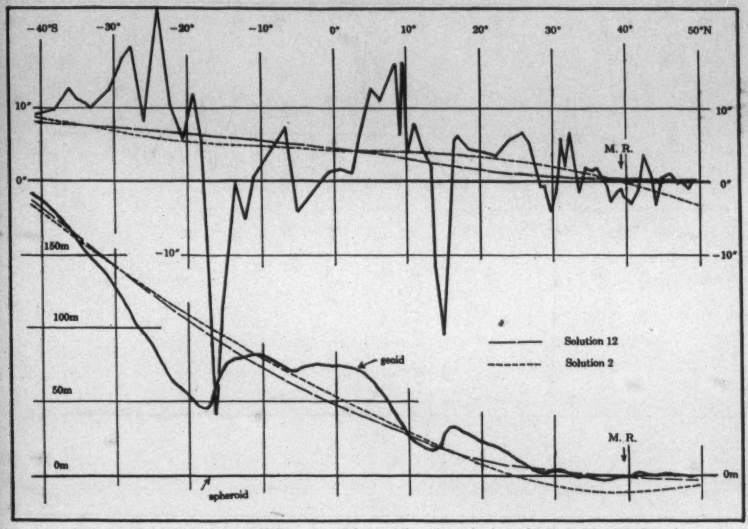


FIG. 2 – North American 1927 Datum, 98th meridian, free-air data; M.R. is Meade's Ranch

a linear combination of Δa and Δe^2 only can be obtained, since the coefficients of these unknowns are not independent of each other.

The general observation equation for a meridional arc is

$$\xi_i = \xi_1 + \frac{\Delta a_0}{a_0}(B_i - B_1) + \Delta e^2\left\{I(B_i - B_1) - \sum_{k=2}^{i}(B_k - B_{k-1})\,[\mathrm{II}\cos 2B_{m_k} - \mathrm{III}\cos 4B_{m_k} + \mathrm{IV}\cos 6B_{m_k}]\right\} + (\varphi_i - B_i) - (\varphi_1 - B_1) \quad (A)$$

for $i = 2, 3, \cdots, n$; and for $i = 1$: $\xi_1 = \xi_1$.

where

B_i = geodetic latitude at point i
φ_i = astronomic latitude at point i
$B_{m_k} = \dfrac{B_{k-1} + B_k}{2}$
a_0, e_0^2 = parameters of given ellipsoid
$a = a_0 + \Delta a \qquad e^2 = e_0^2 + \Delta e^2$
ξ_i = residual of observation equation for meridian
$\mathrm{I} = -\frac{1}{4} - \frac{3}{16}e_0^2 - \frac{15}{512}e_0^4$
$\mathrm{II} = \frac{3}{4} + \frac{3}{4}e_0^2 + \frac{45}{64}e_0^4$
$\mathrm{III} = \frac{15}{16}e_0^2 + \frac{15}{32}e_0^4$
$\mathrm{IV} = \frac{35}{64}e_0^4$

The general observation equation for a parallel is

$$\eta_i = \eta_1 + \frac{\Delta a}{a_0}(L_i - L_1)\cos B + \Delta e^2(L_i - L_1)\frac{\sin^2 B \cos B}{2}(1 + e_0^2\sin^2 B + e_0^4\sin^4 B) + (\lambda_i - L_i)\cos B - (\lambda_1 - L_1)\cos B \quad (B)$$

where

$i = 1, 2, 3, \cdots, n$
L_i = geodetic longitude at point i
λ_i = astronomic longitude at point i
B = latitude of parallel
η_i = residual of observation equation for parallel

The meridional observation equations in the above form were determined to hold for arc segments up to 3° in length. As mentioned before, this criterion was adhered to, with only a few exceptions.

In addition to obtaining solutions for meridians and parallels separately, the sets of observation equations (A) and (B) were combined to give what is termed a 'cross solution.' Another type of solution was obtained by holding the flattening f fixed at the value of 1/297. The results of 36 individual solutions are listed in Table 2.

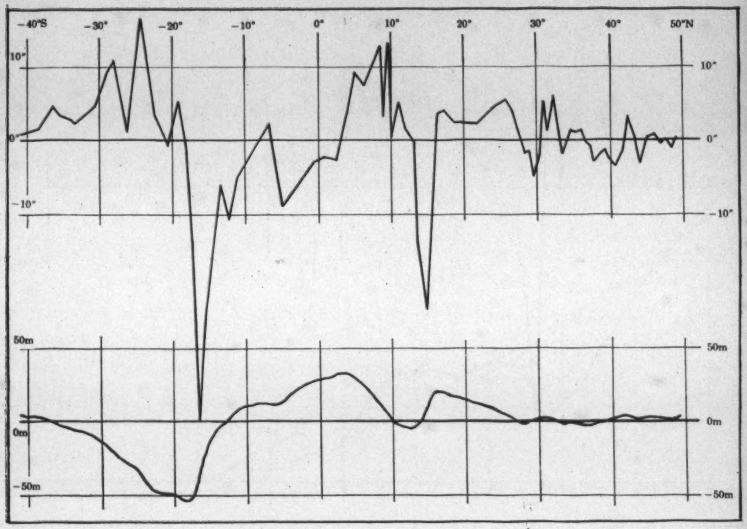


FIG. 3 – America, 98th meridian, free-air Solution 12, $f = \frac{1}{297}$, $a = 6378150$ m

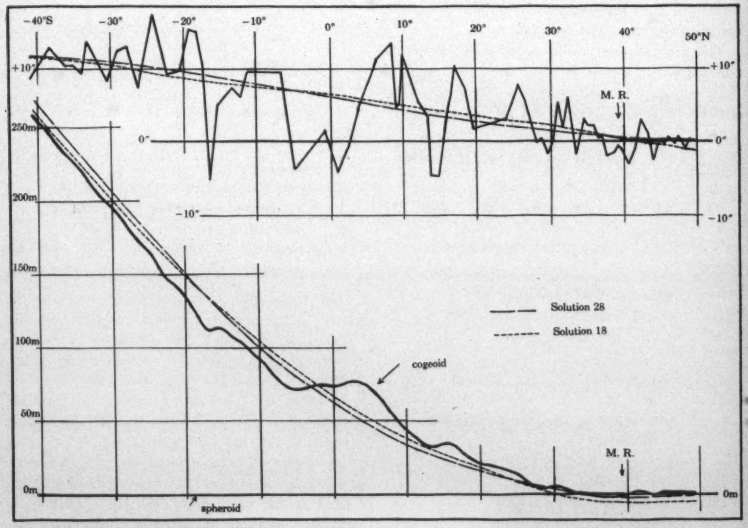


FIG. 4 – North American 1927 Datum, 98th meridian, isostatic data; M.R. is Meade's Ranch

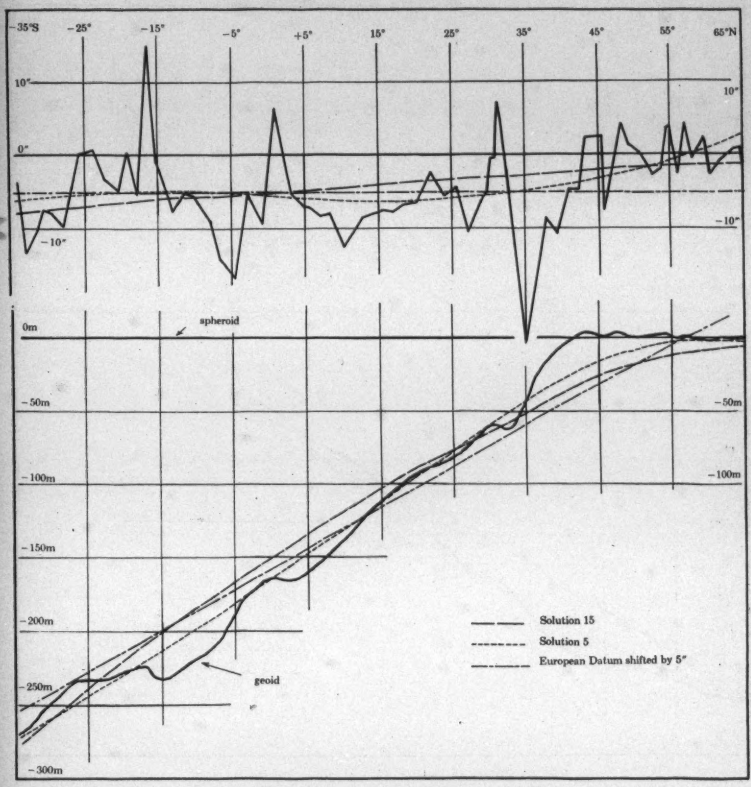


FIG. 5 – European Datum, 24th meridian, free-air data

The uncertainties in the table are all root-mean-square errors. The uncertainities in parentheses in the Column *a* were raised by an additional uncertainty, taken from Table 1 of *Jeffreys* [1948], to include the systematic error in the data due to geoidal undulations along the arc. The column headed σ contains the standard deviations of the residuals of the least squares solutions in seconds of arc.

Geoidal profiles—Figure 2 represents graphically the given material on North American 1927 Datum along the 98th meridian from about 50°N to 40°S. The upper part of the figure shows the astrogeodetic deflections, and the lower part their integration into geoidal heights above the Clarke 1866 spheroid. Between 50°N and 30°N in the United States, both the deflections and the geoidal heights appear more or less as random deviations from the reference line, indicating a good fit of the reference ellipsoid. Going south, however, this fit deteriorates systematically, indicating that there is too much curvature in the present North American datum.

Figure 3 represents one of the solutions with f held fixed at 1/297 in Table 2, and shows, by comparison with Figure 2, the improvement of the values derived here over the old values. The residuals of the least-squares Solution 12 of Table 2 are the new deflections plotted in the graph above, and the corresponding geoidal heights are shown

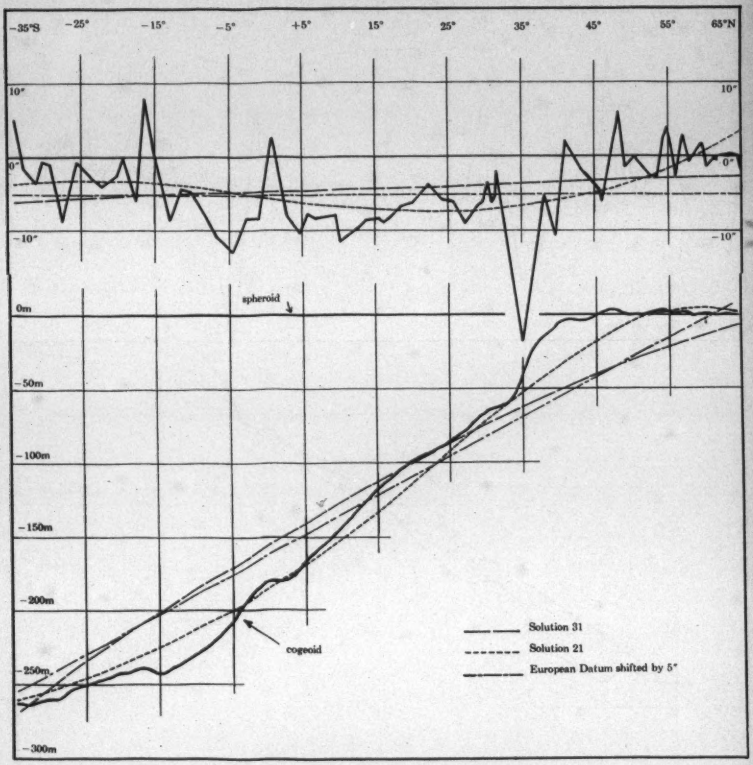


FIG. 6 – European Datum, 24th meridian, isostatic data

below. Within the United States, the difference from Figure 2 is hardly noticeable, but towards the south the deflections are less positive than before and the geoidal heights remain within ±50 m.

Another way of looking at the improvement achieved is to think of the outline of the geoid as a rigid line as, for example, in Figure 2, and then plot the reference line of Figure 3 in relation to it. This viewpoint was taken in sketching the broken line pertaining to Solution 12 into both parts of Figure 2. The shift between the old and new geodetic values along the arc can be read off approximately in the graph of deflections as the distance between the broken and the original straight reference line. The decrease in curvature of the new spheroid against the old may be visualized by comparing the two reference lines in the lower graph, where the new broken line follows the general outline of the geoid much closer than the old straight line.

The second broken line in Figure 2, pertaining to Solution 2, where the flattening f was permitted to vary freely for a best fit, was sketched in to demonstrate the relatively small difference in goodness of fit between these two solutions compared to the big improvement both of them achieve over the original datum represented by the unbroken zero line.

Figure 4 is to be interpreted in the same way as Figure 2, using isostatic instead of free-air data. Figures 5 and 6 parallel Figures 2 and 4 for the

Eastern Hemisphere. In each case they illustrate the relation of two solutions (one with f held fixed at 1/297, and the other with f determined by the best fit) to the original datum. The European Datum, apparently, is also quite a good fit within the area for which it was devised, and deteriorates when applied to Africa. Obviously, there is not enough curvature in the present European datum when extended there. Both new solutions are an improvement for the greater part of the arc from 35°N to 35°S, at the expense of the European area itself.

Because of the current interest in the suitability of the Hayford ellipsoid for the European Datum, the question of an improved orientation with parameters held fixed was investigated. This led to a meridional shift of approximately 5″ to the south. The effect of such a shift is shown graphically in Figures 5, 6, 7. It can be seen that, while not quite as good as the two solutions with variable parameters discussed before, it contains the bulk of their improvement. Figure 7 also gives the variation of a 6½″ shift (broken line), which has less of an over-all slant than the unbroken 5″ line and, therefore, appears to be a better fit from about 50°N to 25°S at the expense of northern Europe. It should be noted in this connection that the conventional condition $\sum v = 0$ of the least squares treatment for a best fit appears graphically as the condition that the two endpoints of the geoidal profile have the same elevation. Figure 7 seems to indicate that this condition puts undue significance on the particular endpoints of an arc.

Composite solutions—To derive a best fitting ellipsoid of revolution from the various individual solutions, an average is taken with weights based on the uncertainties of the unknowns.

The values for f according to Table 2 seem to fall into two groups, $<1/297$ for the Eastern Hemisphere and $>1/297$ for the Western Hemisphere. Their range is too wide to contribute to our knowledge of the Earth's flattening, which is quite well known from other sources. *Heiskanen* [1926] gives $f = 1/297$ as a mean value from five determinations, three from gravity and two from precession. The same value was adopted in 1911 for all astronomic work. Other modern determinations disclose a range of 1/296.85 [*Jeffreys*, 1948] to 1/298.4 [*Zverev*, 1950]. As a basis for the averaging process, therefore, the value of 1/297 was chosen with an uncertainty of ±1 in the denominator, in order to indicate the rate of change in the result, if another value for f should be accepted. The

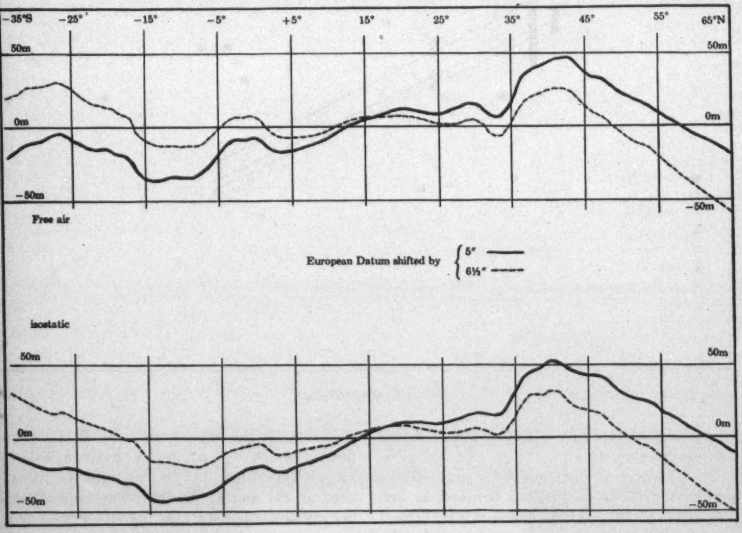


FIG. 7 – Shifted European Datum

TABLE 3 – *Results from combinations of 'crosses'*[a]

Crosses	Free air			Free air with Jeffreys' component			Isostatic		
	$a' \pm u_a$	$\pm u_f$	$\pm u = \sqrt{u_a^2+u_f^2}$	$a' \pm u_j$	$\pm u_f$	$\pm u = \sqrt{u_j^2+u_f^2}$	$a' \pm u_a$	$\pm u_f$	$\pm u = \sqrt{u_a^2+u_f^2}$
One cross from each hemisphere:									
98° + 24°	235 ± 30	95	100	225 ± 55	95	110	270 ± 20	105	105
Pacific + 32°	260 ± 25	90	95	250 ± 50	95	110	300 ± 20	100	100
Pacific + 24°	250 ± 30	90	95	245 ± 50	95	110	285 ± 20	100	100
98° + 32°	250 ± 25	95	100	230 ± 55	95	110	290 ± 20	105	105
Western Hemisphere:									
Pacific + 98°	185 ± 35	105	110	185 ± 60	105	120	240 ± 20	105	110
Eastern Hemisphere:									
24° + 32°	275 ± 25	85	90	275 ± 50	85	100	335 ± 20	95	100
All four crosses	250 ± 20	95	95	240 ± 40	95	100	285 ± 15	100	100

[a] 'Cross' = meridian named, combined with the parallel in its hemisphere (44° or 52°, respectively), for example, 98° means 98th meridian & 44th parallel.

$a = 6378000 + a'$

u_a = uncertainty of least squares solution for $f = 1/297$

u_f = uncertainty due to uncertainty of ±1 in $1/f$

$u_j = u_a$, augmented by Jeffreys' component

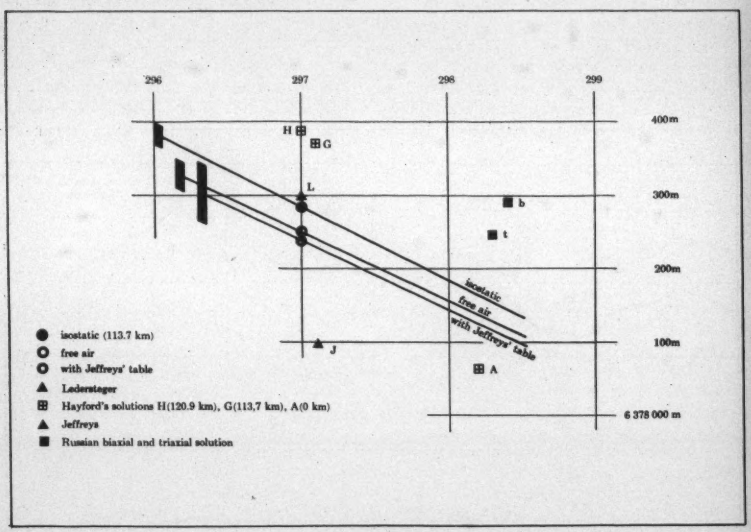


FIG. 8 – Comparisons

effect of this uncertainty is treated as if it were a root-mean-square error.

The observation equations (A) and (B) are based on a linear relationship between Δa and Δe^2. The dependence of the values of a in Table 2 on the values of f (more accurately, of e^2) can, therefore, be illustrated graphically by a straight line, of which two points are given in Table 2 for each meridian by the two results for $1/f$ fixed at 297 and $1/f$ derived. The slope of that line can be computed simply from these two points, or, alternatively, from the normal equations of

the least squares solution. The equations of these straight lines for all cross solutions are given in (C)

Free air

$$\left.\begin{aligned}
&\text{(1) Pacific m. + 44th p.:}\quad a' - 45.47e' = 212 \pm 47 \quad (78)\\
&\text{(2) 98th m. + 44th p.:}\quad a' - 48.27e' = 150 \pm 53 \quad (89)\\
&\text{(3) 32nd m. + 52nd p.:}\quad a' - 39.07e' = 284 \pm 32 \quad (70)\\
&\text{(4) 24th m. + 52nd p.:}\quad a' - 38.42e' = 270 \pm 35 \quad (71)
\end{aligned}\right\}\ \text{(C)}$$

Isostatic

$$\left.\begin{aligned}
&\text{(5) Pacific m. + 44th p.:}\quad a' - 45.47e' = 255 \pm 27\\
&\text{(6) 98th m. + 44th p.:}\quad a' - 48.27e' = 219 \pm 30\\
&\text{(7) 32nd m. + 52nd p.:}\quad a' - 42.54e' = 344 \pm 27\\
&\text{(8) 24th m. + 52nd p.:}\quad a' - 42.26e' = 326 \pm 32
\end{aligned}\right\}$$

where

$$a' = a - 6378\,000$$

$$e' = [e^2 - (.0067226700)](10^5)$$

m. = meridian

p. = parallel

It can be seen at a glance that $e' = 0$ gives the value for a listed in Table 2 for $1/f = 297$; and insertion of the appropriate value for e^2 will give the other value listed there.

The possible combinations, using the same data only once, are given in (D)

Free air

$$\left.\begin{aligned}
&\text{(1) + (3): } a' - 41.13e' = 261 \pm 26\\
&\text{(1) + (4): } a' - 40.94e' = 249 \pm 28\\
&\text{(2) + (3): } a' - 41.48e' = 249 \pm 27\\
&\text{(2) + (4): } a' - 41.35e' = 234 \pm 29
\end{aligned}\right\}\ \text{(D)}$$

Free air with Jeffreys' uncertainties

$$\left.\begin{aligned}
&\text{(1) + (3): } a' - 41.93e' = 252 \pm 52\\
&\text{(1) + (4): } a' - 41.61e' = 244 \pm 53\\
&\text{(2) + (3): } a' - 42.61e' = 232 \pm 55\\
&\text{(2) + (4): } a' - 42.25e' = 223 \pm 55
\end{aligned}\right\}$$

Isostatic

$$\left.\begin{aligned}
&\text{(5) + (7): } a' - 44.01e' = 300 \pm 19\\
&\text{(5) + (8): } a' - 44.16e' = 284 \pm 21\\
&\text{(6) + (7): } a' - 45.13e' = 288 \pm 20\\
&\text{(6) + (8): } a' - 45.54e' = 268 \pm 22
\end{aligned}\right\}\ \text{(D)}$$

The insertion of a value e' corresponding to $f = 1/(297 \pm 1)$ gives the composite solutions listed in Table 3, rounded to the nearest five meters. The two contributions to the final uncertainties are listed separately: The first, u_s, stems from the least squares solution for $f = 1/297$; when augmented by the Jeffreys uncertainty, this is denoted by u_j; the second, u_f, follows from the uncertainty of ± 1 in the denominator of f, and is the dominant factor in the final uncertainty, $u = \sqrt{u_s^2 + u_f^2}$ or $\sqrt{u_j^2 + u_f^2}$, as the case may be. In addition to the solutions from equations (D), Table 3 also lists composite solutions for each hemisphere and for all four crosses.

As a single value, an average of 6,378,260 ± 100 m may be taken. Figure 8 shows the final results as a function of f, with the uncertainties from the least squares solutions indicated as vertical bars. The figure also shows a comparison with results obtained by Hayford, Jeffreys, Ledersteger, and Krasovskiy.

Discussion

Isostasy—The effect of the isostatic reduction of the given deflections may be seen by comparison of Figures 2 and 4, and Figures 5 and 6. In America (Figures 2 and 4) the largest peaks in the graph of deflections were cut down by isostasy. The corresponding most conspicuous holes and humps of the geoid have been smoothed out. A hump in Colombia and a slight relative depression in Peru still persist. In the Eastern Hemisphere (Figures 5 and 6), the outline of the geoid has been altered in some small details but on the whole the characteristic features persist: a big hump in southern Europe, (which is in agreement with *Ledersteger's* [1951, p. 10] remark that the crest of the geoid in Europe is south of the Alps and lies, in a longitude of about 20°, at the latitude of about 43°); the slope of that hump quite steep across the Mediterranean, less steep towards the north; a smaller hump in Tanganyika-Uganda with relative depressions in the Rhodesias and Uganda. Thus isostasy, as used here, has had little effect on the Europe-African arc while it did quite well in America. On the basis of the results obtained here there seems to be no convincing reason for preferring the

TABLE 4 – *Comparisons*

Solution	a	$1/f$
Hayford, isostatic	6,378,388 ± 27	297.0 ± 0.74
Hayford, free-air	6,378,062 ± 33	298.2 ± 1.02
Jeffreys, free-air	6,378,097 ± 116	297.10 ± 0.36
Krasovskiy, triaxial	6,378,245 ± 15	298.3 ± 0.4
Krasovskiy, biaxial	6,378,295 ± 16	298.4 ± 0.4
Ledersteger	6,378,298 ± 34	297
This report, free-air	6,378,240 ± 100	297 ± 1
This report, isostatic	6,378,285 ± 100	297 ± 1
This report, composite	6,378,260 ± 100	297 ± 1

Note: All uncertainties are root-mean-square errors.

isostatic solutions over the free-air solutions, or vice versa.

Shift of European Datum. The shift of about 5″ to the south, suggested by this study of the Europe-Africa arc, agrees with other recent determinations of this shift [*Fischer*, 1954; *Wideland*, 1955], derived from gravimetric material. This supports the idea that determinations from gravimetric and astro-geodetic material, if available over an area sufficiently extended, will tend to yield the same results.

Comparison with other solutions—Table 4 compares some recent solutions with the solutions of this report. Note that the uncertainties are not strictly comparable due to the fact that they are based on different hypotheses as well as different data. For example, if the uncertainty of ±1 in $1/f$ in the solution of this report were reduced to ±.5, the uncertainty in a would drop to about 60 m.

Table 4 and Figure 8 seem to show that Hayford's value of a is too large, and Jeffreys' value too small. The former conclusion is accepted at present by most geodesists, and is believed due to the fact that Hayford used data only from the United States, and that he gave too much weight to deflections based on azimuths, which are considered less reliable than longitude deflections [*Schmid*, 1953]. On the other hand, Jeffreys' value can be ascribed to the small values from the scattered arcs which were the chief ingredients in his solution for a.

Triaxiality—Table 3 shows that the semi-major axis for the Eastern Hemisphere is about 100 m longer than for the Western Hemisphere. This result should not be interpreted as presenting information on triaxiality. Quoting the lengths of axes alone may be misleading, because these meridional ellipses may not fit together to form an ellipsoid at all. The figures computed here under the assumption of $f = 1/297$ refer to ellipses of equal shape but of different sizes. Such ellipses cannot form a triaxial model, because their minor axes differ by the same ratio as their major axes.

If, however, we consider the solutions in Table 2 with the parameters determined simultaneously, then we find that the ellipses best fitting the Western Hemisphere are flatter and have a longer semi-major axis than those for the Eastern Hemisphere. This situation remains the same even if a slight deformation under the linear relationship between a and f mentioned before is enforced, in order to obtain the same semiminor axis for a triaxial model. Thus, the present material puts the bulge of that model in the Western Hemisphere. This is in contrast to historical discussions on triaxiality, obtained from gravity material as well as from arc measurements. While the exact location of the major axis of the equatorial ellipse varies with different investigators, they all place it somewhere on the European side.

These comments, however, should not be construed as advocating triaxiality with a shifted bulge. It is realized that only a thorough investigation could decide on the question of triaxiality as opposed to local undulations best described as deviations from biaxiality.

The fact that the different determinations of a bulge stem from different material seems to support *Jung's* [1954] viewpoint. In his statistical analysis of the available gravity material he points out that the variations of gravity are too diversified to be described sufficiently by the hypothesis of triaxiality. Isotov used this hypothesis in the recent Russian determination of the figure of the Earth; *Krasovskiy* [1955, p. 479], however, remarked that, although triaxial corrections may, in some very general approximation, describe the undulations of the geoid along a particular area of investigation, there is no physicomechanical basis for the triaxiality of the Earth ellipsoid.

Acknowledgments—Previous mention has been made of the part of F. W. Hough and D. L. Mills in this investigation. In addition, acknowledgment is made to H. C. Fuller and J. W. H. Spencer who directed the adjustments of the Latin American and African material, respectively, into unified geodetic systems, and to Spencer again, under whose direction the AMS UNIVAC performed the bulk of the computations. The preparers of this paper are also greatly indebted to J. A. O'Keefe for helpful guidance and suggestions concerning the theoretical problems involved.

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Orographic Rainfall Distribution with Application to Hawaii

LEDOLPH BAER

Abstract—It is shown that the hydrostatic equation is sufficient to explain a distribution of isohyets on a mountain. The particular case of the logarithmic spacing in Hawaii is discussed and a more general form of the distribution equation is derived.

Introduction—Although there are many published papers on orographic precipitation [for example, *Ono*, 1925; *De Boer*, 1950; *Doporto*, 1927], none explains the question of logarithmic distribution of isohyets in the Hawaiian Islands. *Leopold* [1951] shows a map of mean annual rainfall for this area, and he observes:

"Of particular importance is the manner in which rainfall amounts increase inland from the coast. It will be noted in Figure 1 that when the values of the isohyets are chosen as a geometric progression, the isohyets so drawn are nearly equally spaced on the map. This is an important characteristic of the rainfall and presumably is related to the rate of increase of efficiency of the precipitation producing factors. In contrast, the precipitation in the mountains of the western United States is nearly a linear function of altitude."

These relationships are also evident on *Halstead* and *Leopold's* [1948] monthly maps of median rainfall in Hawaii, and the particular problem is evident in other papers [*Landsberg*, 1951; *Wentworth*, 1946]. The author will first discuss the Hawaiian phenomenon and then expand to the more general case, because the Hawaiian case has been more intensively studied and is simpler. An agricultural economy has necessitated better than average gaging [*Halstead* and *Leopold*, 1948; *Stidd* and *Leopold*, 1951], and because of its importance, the Hawaiian climate has been the subject of many papers and an entire monograph [*Hewson*, 1951; *Solot*, 1948, 1950; *Riehl*, 1949].

In Hawaii, the vertical distribution of moisture beneath the trade inversion shows the relative humidity is approximately constant [*Riehl* and others, 1951]. Therefore, the same lift is needed to cause condensation of the air, no matter what the level, as long as it is below the persistent trade wind inversion. This is the basis of a later assumption of a vertically constant mixing ratio decrease from the precipitation W for Hawaii. This paper will show that the unusual vertically constant relative humidity is a basic reason for the islands' pecular rainfall distribution.

Symbols—The following terminology is used.

C = $(W - w)/(P_0 - P)$ = change of W with pressure
D = rainfall depth
D_c = rainfall depth when W = constant
D_L = rainfull depth when $W = w - C(P_0 - P)$
g = acceleration of gravity
P = pressure at upper level (variable)
P_0 = initial pressure (lower level)
R = universal gas constant
T = mean virtual temperature
W = ρ_w/ρ = mixing ratio decrease at a level caused by precipitation
w = mixing ratio decrease at the initial level
Z = height lifted
z = any altitude
ρ = density of moist air
ρ_a = vapor density after condensation
ρ_b = vapor density before condensation
ρ_w = mass precipitated from a unit volume of air.

Derivations—The computation of rainfall can be accomplished from measurements of the total moisture content of the atmosphere before and after the period of rainfall [*Showalter*, 1944]. That is to say, $\rho_w = \rho_b - \rho_a$ for any particular increment of atmosphere. Further, since one gram of water occupies one cubic centimeter

$$D = \int_0^Z \rho_w \, dz \tag{1}$$

The hydrostatic equation is

$$dp = -\rho g \, dz \tag{2}$$

and substituting from it for dz in (1)

$$D = -\int_{P_0}^{P} (\rho_w/\rho g) \, dp \tag{3}$$

Considering g constant and inverting the limits

$$D = (1/g) \int_P^{P_0} W \, dp \tag{4}$$

which is of the same form as *Solot's* [1939] expression for precipitable water in the atmosphere.

Eq. (4) may be integrated when W = constant

and sometimes when $W = F(P)$. First, consider the case of Hawaii where W = constant. Then

$$D_e = (W/g) \int_P^{P_0} dp = (W/g)(P_0 - P) \quad (5)$$

Substituting in the hydrostatic equation for ρ from the ideal gas law

$$dp/p = (-g/RT)\, dz \quad (6)$$

$$\int_{P_0}^{P} d(\ln P) = (-g/RT) \int_0^z dz \quad (7)$$

$$\ln P/P_0 = (-gZ/RT) \quad (8)$$

or

$$P = P_0 e^{(-gZ/RT)} \quad (9)$$

Substituting in (5)

$$D_e = (W/g)P_0[1 - e^{(-gZ/RT)}] \quad (10)$$

A logarithmic distribution of rainfall, D_e, is evident from (10) and thus gives an explanation for the Hawaiian phenomenon.

For the more general situation where W is not required to be a constant, assume as an example $W = w - C(P_0 - P)$. This allows a linear decrease of W with pressure. Other functions could have been chosen, but this one capably illustrates the situation with a simple integral. To have a physical significance $W > 0$ or $C < w/(P_0 - P)$. This therefore applies only to the altitudes in which the precipitation originates. C can be found in any particular case, since, when the air is considered at the altitude where W becomes 0, $C = w/(P_0 - P)$. Substituting in (3)

$$D_L = 1/g \int_P^{P_0} [w - C(P_0 - P)]\, dp$$

$$= w/g \int_P^{P_0} dp - c/g \int_P^{P_0} (P_0 - P)\, dp \quad (11)$$

Substituting D_e from (5) and integrating

$$D_L = D_e - (c/g)(P_0 - P)^2 \quad (12)$$

Eq. (12) shows that depending upon the value of C, almost any distribution of the rainfall D_L is possible.

Discussion—Many variables have not been discussed thus far. For instance, transport of the raindrops by the wind can be of great importance and is quite variable. Other factors such as atmospheric stability, entrainment, availability of condensation nuclei, etc. must affect the final isohyetal pattern. But this derivation has shown that even neglecting such terms, almost any distribution is possible depending only on the available moisture distribution and the amount of lift. Evidently for Hawaii these neglected factors are either small or compensate for errors in assuming W to be constant.

It is understood that it is quite difficult, if not impossible, to measure W and Z. However, very rough approximations can be made from the relative humidity profiles of rawinsonde soundings. The observed isohyets, on the other hand, may aid in reconstructing these values of W and Z for special studies. However, this concept in the qualitative thinking of the hydrometeorologist must not be neglected.

One interesting question that remains only partially answered is the reason for the exponential decrease of precipitation on the higher mountains of Hawaii. This is probably affected by such factors as the inversion height, the gradient level, and the vertical motion profile besides the strong decrease in W. If these equations are modified to allow for variable vertical motions and for time changes, it should be possible to apply them to some cases of convective showers.

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The Use of 'Non-fluence' Lines in Streamline Analysis

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Abstract—Greater accuracy will be attained in streamline analysis if the streamlines are initially drawn in segments each in the direction toward narrower streamline spacing. Lines which divide the map into regions of confluence and diffluence, 'non-fluence' lines, provide both the starting and terminal points for such streamline segments. Such non-fluence lines are the loci of points of orthogonality of rulings (streamlines) and isogons; they are the inflection lines of the set of orthogonal streamlines. In addition to this aid in the more accurate construction of streamlines, they prove useful in the interpretation of streamline maps and in theoretical considerations.

Introduction—Streamline analysis has at least a two-fold interest. It is used in the drawing together of a set of experimental spot observations of a vector field (such as the wind field) in either research or in day-to-day work. It is also frequently of use in the numerical solution of ordinary differential equation problems. This latter use is generally less familiar than the former one to meteorologists. In brief, the idea is this: If an arbitrary value is substituted for the derivative in a first order differential equation, the resulting (non-differential — algebraic would not be strictly correct since the equation may be replete with transcendental quantities), equation defines the locus of all points at which the general solution to the differential equation has a slope equal to that arbitrarily chosen value. It is, in effect, an isogon. As many such isogons may be identified and graphed as one desires. Obviously, given an isogon field derived in this way from a differential equation, one may pass from it to a set of streamlines in exactly the same way one would do so from a set of isogons which are an analysis of spot wind observations. Such an analysis provides a general solution to the equation; boundary conditions will, as usual, define any particular solution. This graphical general solution may be only a preliminary to a more precise numerical one or it may suffice of itself. Of course the main application is to 'messy' problems (such as non-linear ones).

This dual applicability of streamline analysis has had the consequence that contributions to the technique have come from both the 'synoptician' in some field as meteorology or oceanography and, on the other hand, from the pure mathematician. Thus contributions from *Sandström* [1909], *Bjerknes* and others [1911], and *Werenskiolde* [1922] all entered into the ideas further developed and recently published by Palmer and his co-workers (first at UCLA; later in Hawaii). However, some of the topology of singular points came from a mathematician [*Lefschetz*, 1948].

Another reflection of the dual background of streamline analysis is that while the basic idea of this note (summarized in the next section) was arrived at by the author in the course of a numerical solution of a meteorological problem, a check of the literature revealed that it was already known to workers in the field of numerical methods. *Milne* [1953] for example has included it in his textbook.

In what follows, the ideas contained in the summary of streamline techniques prepared by *Palmer* and others [1955], probably the most complete now available in meteorological literature, are assumed known to the reader.

The basic idea—The basic idea of this note is summarized in Figure 1. In a region of difluent streamlines another is to be drawn. The 'true' streamline is indicated by the dashed line; it is, of course, presumed unknown to the analyst. Suppose that he chooses to work from the upper right toward the lower left and makes a small error at point A. Clearly this error will be amplified as the streamline is completed. In contrast, if the analyst had been working from the lower left toward the upper right and had made an error of similar magnitude at point B, the error would be diminished as the streamline was completed. The essential point is that it is better to draw streamlines toward regions of narrowing streamline spacing. This is the case whether the streamlines are being drawn freehand or are being computed stepwise by numerical methods. It is a point of technique usable either in direct streamline analysis, wherein the streamlines are simply 'faired in' so as to be everywhere parallel to the observed vectors, or in isogon analysis, wherein lines of constant direction are first analyzed and then streamlines are prepared by direct analysis of synthetic 'observations,' of any desired number, obtained by ruling the isogons.

Non-fluence lines—A duality exists between the

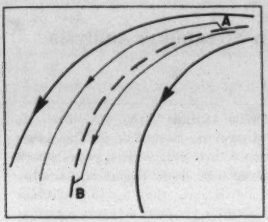

FIG. 1 – The influence of direction of analysis upon errors in the drawing of streamlines

vertical component of the vorticity and the horizontal divergence [*Sherman*, 1952]. One for a given field is plus or minus the other for the velocity field consisting of the normals to the original streamlines and the same speeds.

Inflection lines, that is, lines which are loci of points of zero streamline curvature, play a useful role in the transition from an isogon field to the corresponding streamlines. Such inflection lines are loci of points at which the term of the vorticity dependent upon the wind direction (that is, the curvature term) vanishes. They are determined completely by the direction field alone; they divide it into areas of positive and negative curvature. In practical analysis, these lines are defined as the loci of points at which the rulings are tangent to the isogons. Because of the duality referred to above, it is natural to feel that the corresponding lines for the field of normals might be of significance. This is the case; such lines may reasonably be named 'non-fluence' lines.

A non-fluence line is located in the actual analysis of a field of directions either as an inflection line of orthogonal directions or as the locus of points at which the rulings are perpendicular to the isogons. These lines divide the direction field into areas of confluent and difluent streamlines, that is, into areas of positive and negative 'fluence.' They are the loci of the points at which that term of the horizontal divergence which depends upon the direction vanishes; they are completely determined by the direction field alone.

Non-fluence lines are useful in both theoretical considerations [see, for example, *Sherman*, in press] and in practical streamline analysis. In the latter both the preparation and interpretation of streamline maps are here implied. This stems largelr from the fact that they are loci of extremal streamline spacing; any pair of streamlines will have either a maximum or mimimum distance between them at a non-fluence line. Because of this and in light of the discussion in the previous section, these lines include the best points from which to begin the drawing of streamlines, the points of maximum streamline spacing. Note, however, that while all the most desirable starting points lie along these lines, so too do all the least desirable starting points, namely, those of minimum streamline spacing. It would be possible to give a rule to determine which sections of these lines should be used as starting points in terms of the sense of the change in direction of the rulings (that is, in terms of the sign of the second normal derivative of the wind directions), but this is both cumbersome and unnecessary, as will be seen below.

Again because of the fact that non-fluence lines are places of extremal streamline spacing, they can be used in interpreting completed streamline maps. Such maps normally also have isolines of speed (isovels or isotachs). Were the flow non-divergent, maxima and minima of wind speed along each streamline would be found precisely at the intersection of non-fluence lines and the streamline. Their displacement, up or downstream, is rapidly interpretable in terms of convergence or divergence (and, for low-level maps over the ocean, hence in terms of vertical motions).

The transition from isogons to streamlines—In Figure 2 the transition from a set of isogons to the corresponding streamlines is illustrated. In the upper left the isogons are shown having already been ruled. These rulings represent short sections of

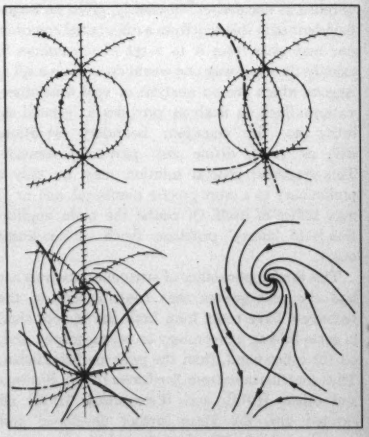

FIG. 2 – The transition from isogons to the corresponding streamlines

streamlines. Points of orthogonal intersection of of these rulings and the isogons have been indicated by the heavy dots; this need not be an actual step in the process.

At the upper right, the non-fluence lines have been entered (as dash-dot lines). In practice, given the requisite man-minutes of effort, this is best done by tracing the inflection lines corresponding to the set of orthogonal streamlines. This requires a second ruling of the isogons and may not be practicable under some circumstances. If necessary these lines can be entered in terms of the orthogonality of the rulings and streamlines; this will be more difficult to do in practice, but may be quicker.

In the lower left of the figure, the inflection lines (heavy solid lines) have been entered as have been some streamlines. Note that four inflection lines radiate from the hyperbolic point. This is quite characteristic.

Since the orthogonal streamlines to a hyperbolic point form yet another one, it is not surprising that there should be the four non-fluence lines. The inflection lines divide the flow about the hyperbolic point into the two pairs of regions of cyclonically and anti-cyclonically curved streamlines characteristic of such a point. Equally characteristic is that there should be four axes of maximum streamline channel inflation about such a point. Thus note that in the neighborhood of a hyperbolic point, the non-fluence lines are not only loci of extremal streamline spacing but, in particular, are known to be of loci of maximum streamline spacing. Thus they provide suitable points for beginning the drawing of streamlines. These streamlines may be extended safely, without violating the principle of the previous section, until they again meet a non-fluence line. This occurs for the streamlines drawn toward the upper left of the sketch being discussed; they have been terminated there. Other streamlines have been drawn toward the same non-fluence line. Some, because of the limitation of the area being mapped, were originated at the edge of the map rather than on a non-fluence line.

At a map point to the west of the cyclonic indraft center, a point of tangency of the streamline field and a non-fluence line is found. Such a point represents the place at which the non-fluence line changes from being a locus of points of maximum streamline spacing (and so a suitable origination point for the drawing of streamlines) to a locus of minimum streamline spacing (and so, in our scheme a terminal point for the drawing of the streamlines). It will usually be possible to begin the analysis in the neighborhood of hyperbolic points and proceed therefrom, with changes in the character of the non-fluence lines being uncovered as the analysis develops. In any event, once a suitable start has been made, the character of the non-fluence lines will be so uncovered thereafter.

It might be pointed out that Palmer and others have given emphasis to the asymptotes of a streamline field. Those streamlines which radiate from a hyperbolic point, initially tangent to the inflection lines, are lines which characterize the field. Parts of them will always be appropriate lines to start with so far as the concepts of this note are concerned; this provides yet another reason for beginning with them.

In the lower right-hand sketch of Figure 2 the final streamlines have been indicated. A selection has been made from those previously drawn. These final ones have been drawn continuously through 'unfavorable' non-fluence line segments. This entails no loss in accuracy since these final lines are tracings or interpolations between the previously determined streamline segments (which were sufficient to define the field).

Discussion—Greater accuracy will result if streamlines are constructed in the direction of narrowing streamline spacing. This may be either up or downstream. Depending upon the care being put into the analysis, this principle should be used to a greater or lesser extent.

For a hurried direct analysis of a set of signals which do not warrant much effort, the analyst might well begin by sketching in a few widely separated streamlines. These will serve to roughly delineate the field. Later streamlines being interpolated should then be drawn in conformity with the principle outlined. After some have been drawn, the analyst (again depending upon the degree of care he wishes to invest) might erase the original sketch streamlines and re-draw them using the principle of always drawing toward a narrowing channel. It might be pointed out, in passing, that the initial drawing of widespread streamlines followed by interpolated ones until the desired streamline concentration is attained is not simply a consequence of the intent to apply the point of this note; it is independently a matter of good technique. This stems from the fact that streamlines do not cross. Suppose that the analyst chose to start at one edge of the map and to draw successively the streamlines 'adjacent' until the opposite edge of the map is reached. Should he at any stage through error displace a streamline into the unanalyzed region, this displacement would be forced upon all the streamlines subsequently drawn, since they could

not go as they should without crossing a previously drawn streamline. This sort of cumulative error is avoided by the scheme of first drawing widespread streamlines then interpolating others.

For a more complete analysis, non-fluence lines would be drawn. This implies that the isogon method is being used. Again a passing remark may not be out of place. The choice between direct analysis and the isogon method is not simply a matter of the density of the initial data; this, though it is sometimes said that with very sparse data one uses the direct method, with more data one goes over to the isogon method. Obviously with a very great amount of data, either method will do; with very little data, neither will do a good job; so the one requiring the lesser effort (the direct method) may as well be used. In the intermediate situation, the choice is a function of the care and time to be invested. The use of the isogon method provides additional readily identifiable points (isogon centers, etc.) from map to map and so provides a convenient means of augmenting spatially sparse data by means of time continuity.

To return, for a more complete analysis non-fluence lines will be prepared. Again, depending upon the time available (in man minutes, the work can be parallel to some extent), these may be constructed as the inflection lines of the orthogonals or, probably less accurately, as loci of points of orthogonal rulings and isogons.

The non-fluence lines involved in this latter more careful approach have uses other than the determination of the best direction for the construction of streamlines. This stems from the fact that they are loci of maximum or minimum streamline spacing. Together with the speed field and streamlines they provide inferences with respect to horizontal divergence.

Summary—More accuracy will be attained in streamline analysis if the streamlines are constructed in segments, each drawn toward narrowing streamline spacing. In order to apply this principle, the analyst must define the areas of streamline confluence and diffluence so that he can chose the direction in which he should analyze. He can do this with varying degrees of care: by defining these areas roughly by visual examination of the map signals, by sketch streamlines or by the use of non-fluence lines, constructed as outlined above.

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A Shoreward Movement of Cool Subsurface Water*

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Abstract—Water temperature measurements over the San Pedro Shelf off Southern California have shown that cool subsurface water may move to the surface at the inner margins of the continental shelf in the absence of wind. The movement of the cool water indicates that it may have a tidal period. Possible mechanisms for this motion include, (1) internal waves, and (2) tidally-generated 'cold spots.' Both are discussed in relation to the observed temperature changes in the San Pedro area.

It is concluded that similar movements of cool subsurface water may occur along any coast regardless of the orientation of the dominant or prevailing winds. Factors of most importance in the development of such upwellings seem to be the range and characteristics of the tide and, perhaps, a properly oriented irregular bottom topography. These observations point to a possible mechanism for the formation of some nearshore fogs, and also show the need for a study of factors other than wind which lead to the rising of cold deeper water over the shelf.

Introduction—Irregular submarine topography of the Southern California shelf may be responsible for unusual temperature variations in the water overlying the shelf [*McEwen*, 1912; *Leipper*, in press]. The physical characteristics and motion of these temperature variations are not well known owing to the lack of adequate measurements during their occurrence.

Bathythermograph casts made by D. F. Leipper and staff members of the Scripps Institution of Oceanography showed that under certain tidal conditions a landward movement of offshore subsurface water occurred in the absence of wind. Water temperatures indicating a similar phenomenon were obtained from a series of bathythermograph casts and from records of the thermograph of the *Velero IV* during the period of July 23, to July 29, 1954. Winds were light or absent during the period in question.

For the purposes of this report a *thermocline* is defined as a region below a surface mixed layer where

$$\text{temperature } (°\text{F})/\text{depth(m)} \geq 1.0$$

Any temperature slope with a value less than unity is called a *temperature gradient*; a zero gradient, of course, indicates isothermal water conditions.

Temperature Measurements over the San Pedro Shelf, July 1954

General statement—On July 29, 1954, an intrusion of cool water intersected the surface near the Los Angeles breakwater and apparently caused the formation of intense localized fog. The water temperature at the Los Angeles Harbor entrance was 64°F, whereas the water temperature seven miles seaward of the entrance was 71.5°F (see Table 1). Five days before, on July 23, the temperature at both localities was 72.5°F. This intrusion of cool water may have been caused by a landward migration of subsurface offshore 'cold spot', or by long-period internal waves of tidal origin.

The vertical distributions of water temperatures on July 23 and 24, along sections extending due south of the Los Angeles Harbor entrance are shown in Figure 1. Although three distinct water types can be determined from the temperature and salinity characteristics, two are important in this report. The first occurs from the surface of the sea to a maximum depth of 40 ft and is an almost isothermal layer of about 33.58‰ salinity and temperature above 71°F. The lateral distribution of this water type, together with its temperature and salinity characteristics, suggests that it originated in the shallow harbor area. The second water type, the one involved in the upward motion described here, occurs beneath the sharp thermocline and has an average salinity of 33.48‰ and temperatures of 64°F and less. Thus, salinity and temperature differences markedly distinguish these two water types.

Rate of shoreward movement—Bathythermograph casts could not be made during the first days following July 24. Nevertheless, a close check on the surface water temperature at the Los Angeles Harbor entrance and at a position seven miles offshore provided a control for computing the rate of approach of individual isotherms. This

* Contribution of the Allan Hancock Foundation No. 178.

TABLE 1 – *Surface water temperatures and average wind data*

Date	San Pedro channel and vicinity			
	Sea surface temperature L.A. Harbor entrance	Wind data		
		L.A. Airport	VELERO IV	Civic Center
1954	°F	knot dir.	knot dir.	knot dir.
July 23	72.5	5.2W	8.0SW	5.6W
July 24	71.5	8.1WSW	10.0W	5.8W
July 25	71.0	7.8SW	...	5.0W
July 26	70.5	6.6WSW	...	5.5W
July 27	70.0	6.6WSW	3.0WSW	5.3W
July 28	68.0	6.7WSW	4.0SW	5.2W
July 29	64.0	5.5WSW	...	4.1W

was accompanied by comparing the time required by the various isotherms to reach the surface. For example, the 64°F isotherm intersected the surface on July 29, after originally being at a depth of 60 ft on July 23; hence it rose 60 ft in 5.5 days.

Factors affecting the observed rate of vertical motion include (1) the 'packing' of the isotherms at the shoreward edge of an intruding water mass (variations in the distance between isotherms may give an impression of a varying rate of rise which does not actually exist) and (2) diurnal heating, which may also mask rising cool water and yield false rates of motion if not considered. In the case of movements of large masses of water under tidal influences, momentum effects may also distort the apparent rates of rise.

Water temperature changes on July 23 to 29, 1954 —The water temperature at the harbor entrance began to decrease on July 25, when a reading of 71.0°F was recorded at 16h00m on *Velero IV's* thermograph. A continual gradual decrease was noted from July 26 to 28. At 16h30m on July 28, the thermograph record indicated a surface temperature of 69°F. The following day, July 29, a dense fog layer approximately 100 ft thick formed at 05h45m and covered the area from 400 yd inside the breakwater to about a mile seaward of the light, and from Point Fermin on the west to Huntington Beach on the east (Fig. 1). Surface water temperature at 11h00m July 29, at the Los Angeles Harbor entrance, was 64°F, and the fog was still dense. Solar heating of the surface water was probably at a minimum, and so it is believed that the low surface water temperature was due to the earlier intersection of the rising 64° isotherm with the surface.

The suggested rate of rise in feet per day computed from the time that each isotherm reached the surface is plotted in Figure 2. The rapid rate of upward motion noted in the first two 24-hr periods through July 25, and in the last 17 hr of the survey appears to be due to the intersection of the closely packed isotherms of the thermocline zone with the surface. An average of 18 temperature readings at the top of the thermocline was 71.3°F. If the reading of 71.5° at 16h00m on July 25 is correct, the top of the thermocline reached the surface at approximately that time. The average thickness of the thermocline was 15 ft, and since the average rate of rise for July 23 and 24 was 15 ft per day, a change in the direction or velocity of the motion of the intruding water must have occurred in order to account for the fact that the bottom of the thermocline did not break through during the next three days. The average rate of rise for July 25 to 28 decreased to slightly more than six feet per day.

It is probable that the actual rate has been affected by diurnal surface heating and mixing of the water in the surface layer. The weather during this period was clear and warm. The corrected curve in Figure 2 has been drawn assuming an average diurnal rise in the surface water temperature of 1.5°F to 16h00m (the actual measured diurnal change was 1.5° on July 23). This does not materially change the shape of the curve from that plotted from the uncorrected temperatures. Thus, it appears that an initial rapid rate of rise, followed by a decrease in rate and then by a second increasing rate, is real.

A variation in the direction and velocity of the cool water intrusion is interesting when compared to the increased tidal action during the period (Fig. 3). The increasing tidal range would allow more and more warm and saline water to issue from the harbor into the shelf area. This flow might mask the rising cold water below the thermocline. However, after the thermocline had broken through to the surface, the increased temperature difference between harbor water and the cooler rising water would probably alter the direction of flow of harbor water, and cool surface conditions for the observed formation of fog would exist. At the same time, the marked temperature gradient would promote the motion of surface water offshore from the area of upwelling, and sufficient momentum might be generated to account for the continued cool surface over which fog remained and thickened appreciably until August 2.

Mechanisms—This shoreward movement of offshore subsurface water appears to be related

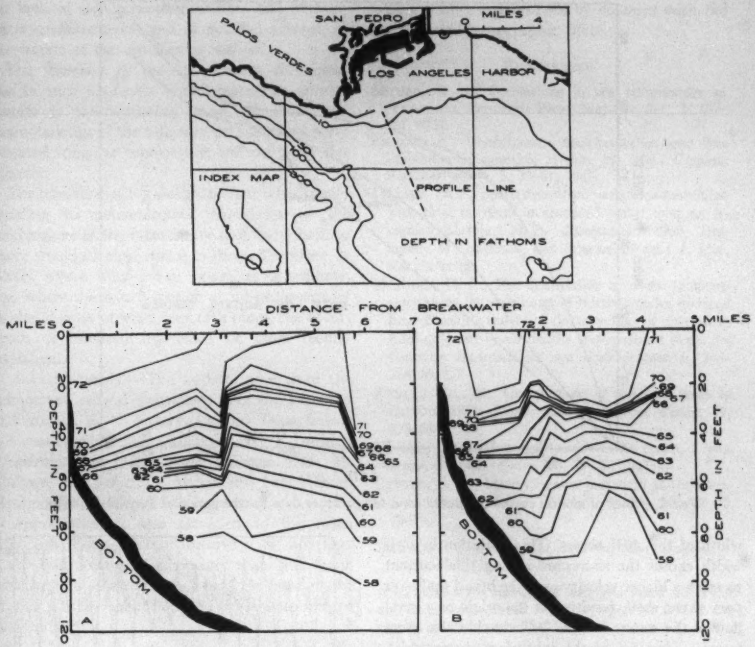

FIG. 1 – Location map and water temperature profiles along the indicated section line (A) July 23, 1954, and (B) July 24, 1954; temperatures from bathythermograms

to the monthly tidal cycle (see Fig. 3). Neap tides occurred on July 22, and in the period under consideration tide ranges were increasing. The absence of appreciable wind preceding and during the period eliminates the classical wind-driven process of upwelling as the origin of the cool water intrusion.

Internal waves of large magnitude and amplitude have been measured along the Pacific coast [*Reid*, 1956]. Assuming the thermoclinal surface indicates the position of an internal wave surface, it is seen that the length would be from two to five miles with a height of 30 to 50 ft. Little is known of the action of internal waves of this magnitude in shelf water.

Arthur [1954] has shown that variations in subsurface water temperatures, similar to those noted by *Leipper* [in press], also occur along coasts with a relatively regular bottom topography. Differential tidal stirrings in the water overlying such a bottom seems unlikely, and the similarity in observed temperature oscillations in these areas may require a common explanation. Internal waves with periods varying from a few minutes to that of diurnal tides may be capable of causing temperature changes of the magnitudes observed, and of a similar period. *Ufford* [1947ab] has demonstrated the existence of such waves along the southern California coast, and *Defant* [1947] had indicated that internal breaking surf can be expected when certain internal waves enter shoal water. A continuous train of internal waves, increasing in amplitude from neaps to springs and resulting in the mixing expectable from breaking waves nearshore, could conceivably account for the observed water conditions in July 1954 over the San Pedro Shelf.

Leipper [in press] has described the formation of dome-shaped subsurface 'cold spots' by tidal action over parts of continental shelves having irregular topography. The formation begins after neaps over areas where a marked difference in the

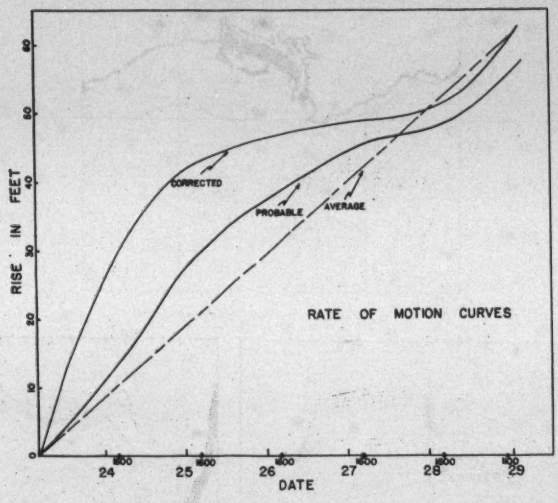

FIG. 2. – Rate of motion curves computed from temperature data for the period of July 23–29, 1954

width of the shelf occurs. This variation in shelf width causes the shoreward-setting tidal current to reach a higher velocity over the broad shallower part of the shelf, resulting in the origin of a gyral flow of the water. Leipper believes that this gyral forms a 'doming' of the subsurface water which increases in magnitude toward springs. It is believed that the resulting subsurface 'cold spots' move in varying directions over the shelf. This irregular motion could account for the variation in the observed rate of rise of the isotherms on July 23 to 29. The dimensions of the cold dome are greatest at springs, and, if there is shoreward movement, the top of the dome may reach the surface. As the tidal amplitude diminishes after springs, the dome-shaped 'cold spot' dissipates. Water temperatures and topography of isothermal surfaces observed since July 1954 make this explanation attractive.

If the mechanism is a constant accompaniment of the tide, its observable temperature effects would decrease or vanish in the winter months in the Southern California area, paralleling the supression of the marked summer thermocline. The temperature changes would be most noticeable in the late spring, summer, and early fall, a period when upwelling is known to be most intense. Detailed oceanographic surveys by the authors over the San Pedro and Santa Monica Shelves show that

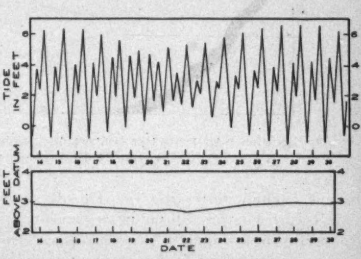

FIG. 3 – Tide data for the Los Angeles Harbor and vicinity from U. S. Coast and Geodetic Survey records for July, 1954

local upwelling occurs during every month of the year. However, several occurrences of cool nearshore water in the summer of 1954 and 1955 had no apparent relation to the contemporary wind directions and velocities.

Conclusions—A shoreward movement of subsurface water by tidal forces may be possible along any coast. Cool water could be brought to the surface regardless of the orientation of shorelines with respect to the prevailing or dominant winds. Internal waves of large amplitude and period may be important factors in the process. The paucity of information of occurrences is probably due to

the lack of simultaneous nearshore and offshore water measurements, and of detailed surveys of the waters of the continental shelves.

The intensity of the temperature differences due to such a process would depend on several factors in the bordering ocean. Of these, the characteristics of the tide, and perhaps a properly oriented irregular topography, are the most significant.

The formation of fog along the coast is frequently puzzling to meteorologists. Knowledge of the mechanisms of the intrusion of cool water next to shore would be most useful to them. Therefore, in places where wind-driven upwelling is unlikely, and where shoreward motion of subsurface water in the absence of wind does take place, the occurrence of localized fog could be more readily explained.

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Variations in the Equatorial Countercurrent in the Central Pacific

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Abstract—Cruise 15 of the M.V. *Hugh M. Smith* consisted of four consecutive lines of oceanographic stations along 140°W longitude between 8°N and 7°S latitude. Geostrophic calculations show that during a five-week period the maximum eastward velocity component in the Countercurrent progressively increased from 63 to 120 cm/sec and the volume of flow increased from 18.3 to 22.6 × 10^6 m^3/sec. In spite of these short-term variations, the Equatorial Countercurrent in the central Pacific is remarkably predictable in latitude and general physical characteristics.

The Pacific Oceanic Fishery Investigations (POFI) of the U. S. Fish and Wildlife Service has been taking oceanographic observations in the central equatorial Pacific since early 1950 [*Sette*, 1954]. This program has been designed to describe the marine physical, chemical, and biological environment, particularly as it relates to the abundance and distribution of tuna. Early oceanographic surveys were planned to provide an understanding of the general circulation features; subsequent studies have been designed to investigate the regions and features thought to be of particular biological importance. *Stroup* and *Austin* [1955] have reviewed the POFI oceanographic programs and list the publications resulting therefrom.

The almost 100 meridional crossings of the central Pacific equatorial currents by POFI vessels demonstrate the over-all persistence of the zonal circulation and show evidence of superimposed transients. Cruise 15 of the POFI oceanographic research vessel, *Hugh M. Smith*, was specifically designed to investigate these short-term variations along 140°W longitude by completing four consecutive station lines; the observed data from this cruise along with the meridional sections and a brief descriptive text were published by *Austin* [1954]. Our paper is based primarily on these data.

For orientation during the following discussion, a typical meridional temperature section across the major equatorial currents is shown in Figure 1. A temperature section from Cruise 11 was chosen for Figure 1 as the similar sections from Cruise 15 did not penetrate the North Equatorial Current. The well-developed 'two-layered' system characteristic of these latitudes throughout the year is evident. The configuration of the isotherms reflects the mass distribution associated with the zonal flow. The Equatorial Countercurrent, as shown by the southward deepening thermocline, flows east (out of the section) between 10°N and 5°N latitude; the west-setting North and South Equatorial Currents lie to the north and south of the Countercurrent with the South Equatorial Current on both sides of the equator. The lower temperatures of the surface layer about the equator are indicative of the divergence and associated enrichment from below, a biologically significant feature of the central equatorial Pacific [*King* and *Demond*, 1953; *Murphy* and *Shomura*, 1953].

It has been shown by *Montgomery* and *Palmén* [1940] that the most probable explanation for the Countercurrent is the downward west-east slope of the sea surface resulting from the westerly stress of the trade wind system. They demonstrate that the Countercurrent is a 'downhill' return flow in the region of the doldrums; here the NE and SE trades converge and rise, resulting, climatologically, in light and variable winds. In the central Pacific between approximately 110°W and 170°W longitude, the mean positions of the doldrums and the Countercurrent agree very closely and exhibit similar seasonal meridional fluctuations, whereas east and west of this region the situation appears more complex and the relationship between wind stress and Countercurrent requires further investigation.

At the time of Cruise 15 (June, 1952) the mean positions of the subtropical anticyclones were as shown in the left-hand panel of Figure 2. The station lines (heavy vertical line) approximately straddle the mean position of the equatorial pressure trough during this period. Normally, during the month of June, the trough is somewhat farther north, centered at 7° to 9°N latitude [*Riehl*, 1954].

The wind direction and speed observed on each of the four legs during Cruise 15 are shown in the right-hand panel of Figure 2. The direction scale centers on 090°T; thus the portion of the curve to the left of center represents winds from the northeastern quadrant, that to the right, winds

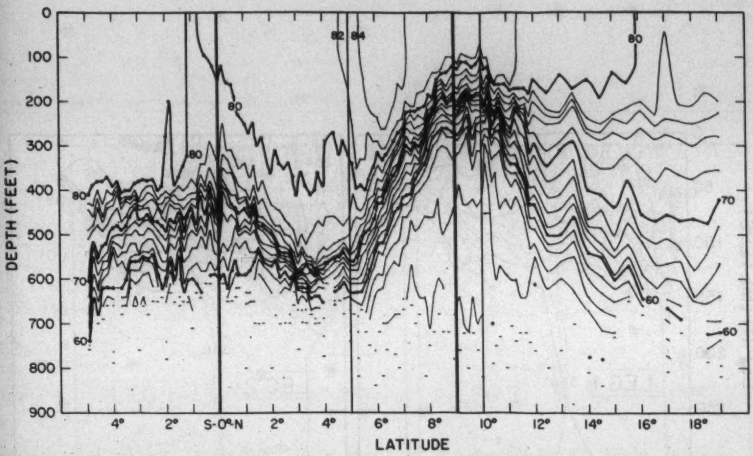

FIG. 1 – Vertical meridional distribution of temperature (°F) from *Hugh M. Smith* Cruise 11, 150°W longitude, September 25 to October 4, 1951; the bold vertical lines denote the meridional limits of the *Hugh M. Smith* Cruise 15 profiles in this paper; the light vertical lines show the computed boundaries of the Equatorial Countercurrent for Cruise 11

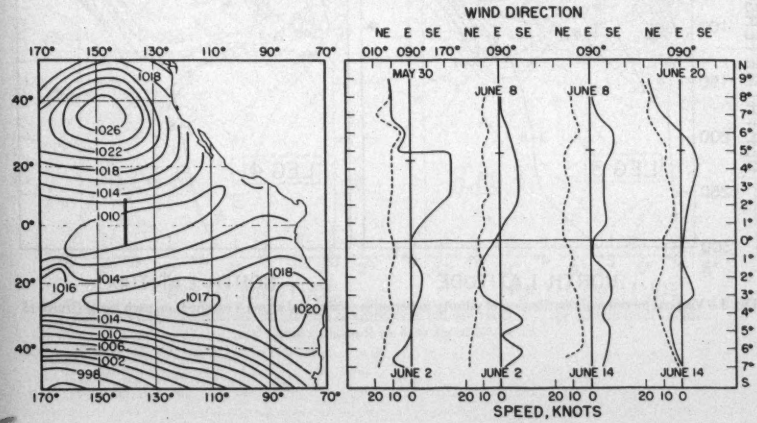

FIG. 2 – (Left panel) Mean atmospheric pressures in mb for June 1952, the positions of the Cruise 15 sections are shown by the heavy black line; (right panel) the true wind direction (solid line) and wind speed (broken line) observed on Cruise 15; both curves are a sighted mean drawn through observations taken at ten-mile intervals; the observed position of the southern boundary of the Countercurrent is shown for each leg by the horizontal dash; the northern boundary was at approximately 10°N, the exact position cannot be determined from the data; the data for the mean June pressure distribution in the northern hemisphere are taken from *U. S. Weather Bureau* [1952]; data for the southern hemisphere are from microfilm records provided by C. E. Palmer, Oahu Research Center, Institute of Geophysics, University of California

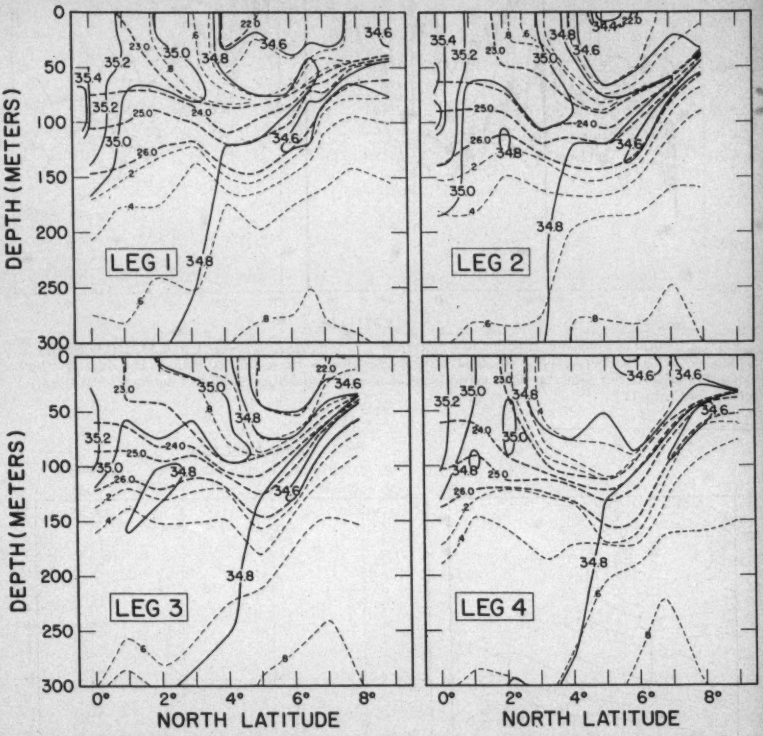

FIG. 3 – Vertical meridional distribution of salinity in per mille (solid) and sigma-t (dashed) on each leg of Cruise 15

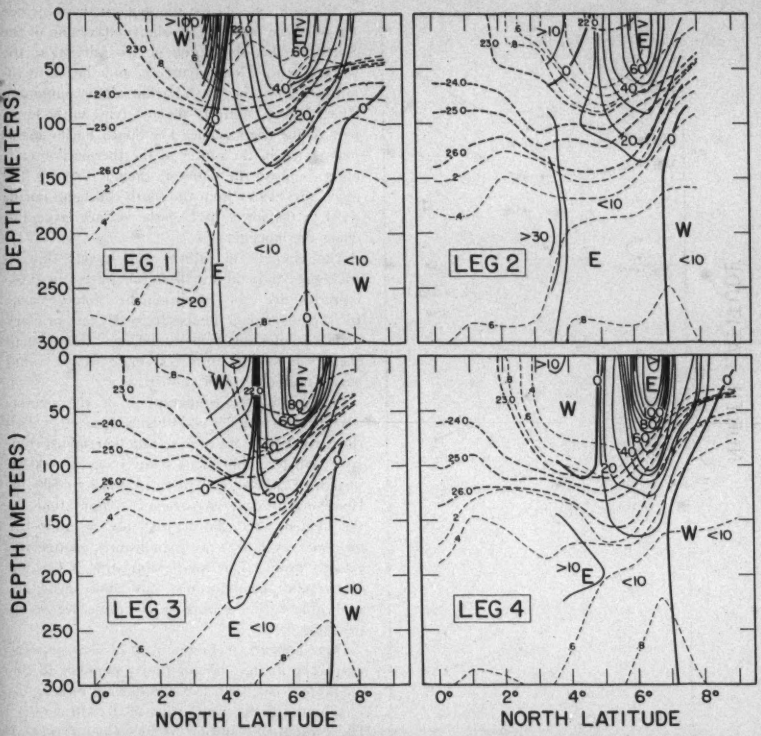

FIG. 4 – Vertical meridional distribution of currents in cm/sec relative to the 400-db level (solid) and sigma-t (dashed) on each leg of Cruise 15

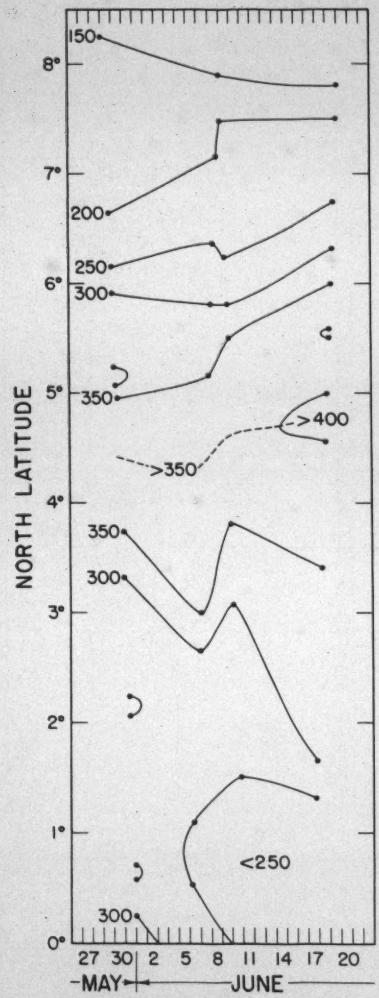

FIG. 5 – Time-latitude plot of depth of the 70°F isotherm; dashed line indicates center of trough at southern boundary of Countercurrent

from the southeastern quadrant. The classical picture of the doldrums is lacking, although there is convergence between the northeast and southeast trades at about 5° or 6°N on the first and fourth legs. At the northern end of the second and third legs the wind direction tends to be easterly.

Variations in the oceanographic features north of the equator are illustrated in Figures 3, 4 and 5. The distribution of salinity superimposed on the sigma-t field (Fig. 3) shows the normal features of the salinity field for this region; these include the northern limit of the salinity maximum of the South Pacific, the region of low salinity at the surface in the Countercurrent, and the southernmost extent of the North Pacific salinity minimum, which here is relatively shallow, lying in the lower part of the thermocline. The South Pacific maximum lying in the center of the thermocline ends abruptly near the equator, though some of the more salty water from the south continues northward in the lower part of the surface layer and upper thermocline.

The changes in salinity are largely due to advection and indicate that the waters in these latitudes are not longitudinally homogeneous. In these regions, temperature is the primary variable affecting density. Thus, these small changes in salinity from section to section would have a negligible effect on density.

Changes in the configuration of the sigmat-isopleths can be followed in Figure 4, together with the current normal to the section determined from geostrophic computations relative to the 400-db surface. Stations on Cruise 15 were to 500 m. However, previous geostrophic computations in this region have shown that use of a deeper reference level does not significantly change the velocity profile. The isovels stop at 3½°N because geostrophic computations are not generally applicable within approximately three degrees of the equator.

There appears, in Figure 4, to be a progressive steepening in the slope of the σ_t isopleths in the Countercurrent, with a corresponding increase in maximum current speed from 63 to 120 cm/sec. The computed transport of the Countercurrent south of 9°N increased from 18.3×10^6 m³/sec to 22.6×10^6 m³/sec from the first to the last section. The contribution of the portion of the Countercurrent north of 9°N would not greatly increase these transports.

To emphasize the time relationship of the four sections, Figure 5 shows a plot of the depth of the 70°F isotherm against latitude and time. In this region, the 70°F isotherm is normally positioned near the center of the thermocline (Fig. 1). The steepening of the slope of the thermocline in the Countercurrent is shown by the 90-mi decrease in the horizontal distance between the 150- and

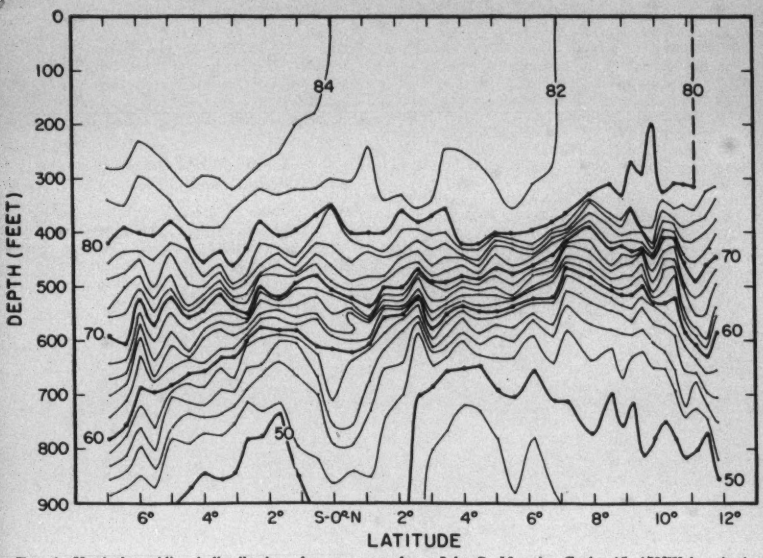

FIG. 6 – Vertical meridional distribution of temperature from *John R. Manning* Cruise 15, 170°W longitude April 28 to June 16, 1953

the 350-ft contours from Leg 1 to Leg 4. Of greater interest in Figure 5 is the evidence that some significant changes of slope in the Countercurrent took place in the relatively short time between the observations on Legs 2 and 3. While, in general, short-term variations in the distribution of mass are not reflected in corresponding velocity changes, it is probable that the changes in the Countercurrent velocity during Cruise 15 are not as regular as suggested by the results of geostrophic calculations shown in Figure 4.

Since the computed currents plotted in Figure 4 indicate only that component of the velocity normal to the sections, that is, the zonal component of flow, some of the apparent variations in speed and volume transport could be caused by north-south meandering in the Countercurrent. While these meanders cannot be ruled out, there has been no evidence of large-scale meandering during POFI's many crossings of the Countercurrent in the central Pacific, or during the recent EASTROPIC expedition, an east-west survey of the current between 160°W and 115°W longitude.

Thus, geostrophic computations show that during the period of Cruise 15 the speed of the Countercurrent doubled within four weeks. Longer-term and more pronounced changes in speed are suggested in other POFI data. On at least one previous occasion (*John R. Manning* Cruise 15) the Countercurrent, as inferred from the slope of the thermocline (Fig. 6), was nearly slack. Compare the slopes of the thermocline (10°N to 5°N) in this figure and in the more typical section shown in Figure 1. Drift of free-floating fishing gear gave further evidence that the Countercurrent was very weak (less than 15 cm/sec). It is interesting that these observations closely followed a period of one of the most striking El Niños in recent times [*Sears*, 1954].

The above discussions demonstrate that there are transients in the central Pacific Equatorial Countercurrent at least of the scale observed. It has not been possible to relate these changes to local wind conditions. Further studies, possibly ocean-wide in scope, are required to determine the causes of these fluctuations.

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Properties of Shoaling Waves by Theory and Experiment

PETER S. EAGLESON

Abstract—Experimental results on the transformation of wave height, length and steepness on a plane beach of 1/15 slope are compared with the small amplitude theory of Airy. The effects of wave shape and beach slope on the applicability of the theory are shown through comparison with these data and with those of former investigators. The theory is found applicable to the prediction of steepness. Additional observations on the transformation of crest height and length are presented and discussed with respect to their influence on the mass-transport velocities.

Introduction—In laboratory studies of beach processes it is convenient to classify the incident wave according to its so-called 'deep water' ($d/L > \frac{1}{2}$) characteristics which by definition are independent of depth. Upon assumption of the deep-water profile form this independence of depth allows complete description of geometry and kinematics through specification of the steepness, H_0/L_0, and the period T.

It is not always desirable, nor indeed possible because of limitations of equipment, to generate the desired wave in its deep-water form in the laboratory. It then becomes necessary to define through theory an equivalent deep-water wave on the basis of measured shallow-water ($d/L < \frac{1}{2}$) characteristics.

The reverse of this problem, the prediction of shallow-water characteristics as a function of depth and given deep-water properties, has been the subject of considerable analytical and of some experimental investigation as summarized below. Unfortunately, the recent theoretical results of *Eckart* [1951], *Stoker* [1947], *Biesel* [1951] and others are not readily converted for the purpose on hand while the results of various experiments by *Wiegel* [1950], *Iversen* [1953], and others seem inconclusive when correlated on the basis of the classical small-amplitude theory.

Notations—The following symbols are used.

a_1 = wave-crest height, ft
c = subscript referring to wave crest
C = wave celerity, ft/sec
d = local water depth measured from still-water level to the bottom, ft
E = wave energy per unit of surface area, ft lb/ft²
g = acceleration due to gravity, 32.2 ft/sec²
H = wave height, crest to trough, ft
k = mean diameter of beach roughness
L = wave length, ft
n = ratio of group velocity to wave velocity as specified
o = subscript referring to deep water
P = power transmitted by a wave per foot of crest width, ft lb/sec ft
T = wave period, sec
$\overline{U}$ = mass transport velocity, ft/sec
γ = specific weight, lb/ft³
θ = angular displacement in wave, origin as specified, radians
$\pi = 3.14\ldots$.

Results of previous work—Rayleigh [1877] was one of the first to deal theoretically with the transformation of shallow-water waves moving into shoaling water. He introduced the idea of energy partition which states that the power per unit of crest width in any depth of water may be given by

$$P = nEC \tag{1}$$

For the progressive wave of finite amplitude it can be shown [*Gerstner*, 1802] that

$$E = \frac{\gamma H^2}{8}\left[1 - \frac{\pi^2}{2\tanh^2\frac{2\pi d}{L}}\left(\frac{H}{L}\right)^2\right] \tag{2a}$$

in which the kinetic energy is slightly greater than the potential.

For waves of low steepness this reduces to

$$E = \gamma H^2/8 \tag{2b}$$

which, in a non-dispersive medium, is divided equally between potential and kinetic energies.

The energy-transformation factor n accounts for the fact that in deep water, where particle orbits are circular and the kinetic energy along any horizontal plane through the fluid is a constant, only the potential energy travels with the wave. As the wave shoals, more and more of the kinetic energy also travels with it, n approaching unity as the wave becomes a purely translatory phenomenon.

For the small amplitude wave

$$n = \frac{1}{2}\left[1 + \frac{\frac{4\pi d}{L}}{\sinh\frac{4\pi d}{L}}\right] \tag{3}$$

Since the rate of energy transmission across any two sections must be a constant under the assumption of negligible dissipation and reflection,

$$[nEC]_0 = [nEC] \tag{4}$$

which, for low steepness, may be written

$$\frac{H}{H_0} = \left[\frac{1}{2}\cdot\frac{1}{n}\cdot\frac{C_0}{C}\right]^{\frac{1}{2}} \tag{5}$$

Development of a usable expression for transformation of wave characteristics requires expression of the wave celerity in terms of its geometrical properties. Of all the existing wave theories, Stokes' irrotational theory for waves of finite height comes closest by experimental evidence [*Mason*, 1948] to representing actual wave kinematics in water of constant depth. Stokes found the speed of propagation to the third approximation to be given by

$$C^2 = \frac{gL}{2\pi}\tanh\frac{2\pi d}{L}\left\{1 + \left(\pi\frac{H}{L}\right)^2\left[\frac{2\left(\cosh\frac{4\pi d}{L}\right)^2 + 2\cosh\frac{4\pi d}{L} + 5}{8\left(\sinh\frac{2\pi d}{L}\right)^4}\right]\right\} \tag{6}$$

Neglecting the effect of height, (6) reduces to that given by *Airy*'s [1842, p. 289] theory

$$C^2 = \frac{gL}{2\pi}\tanh\frac{2\pi d}{L} \tag{7}$$

which, for deep-water conditions reduces further to

$$C_0^2 = \frac{gL_0}{2\pi} \tag{8}$$

Assuming the celerity of a wave at any depth on a sloping bottom to be given by (7) for the same depth on a horizontal bottom, (5) becomes

$$\frac{H}{H_0} = \left[\frac{2\cosh^2\frac{2\pi d}{L}}{\frac{4\pi d}{L} + \sinh\frac{4\pi d}{L}}\right]^{\frac{1}{2}} \tag{9}$$

and (7) and (8) yield

$$\frac{L}{L_0} = \tanh\frac{2\pi d}{L} \tag{10}$$

Iversen [1953] measured the transformation of height for a wide range of initial steepness on slopes of from 1/10 to 1/50 and made a comparison with (9). He found the experimental height to fall well below the theoretical in the region of minimum height and then to rise to values greater than theory at lower d/L.

In addition, *Wiegel* [1950] made measurements of wave length in the shoaling region. His investigations, using slopes of 1/10.8 and 1/20, were chiefly concerned with comparisons of profile with the extrapolated trochoidal theory, but in addition, included comparisons of wave length and steepness transformation with Airy's theory. Wave length (and thus celerity) agreed well with theory over a range of H/L from 0.009 to 0.05 regardless of beach slope. However, the experimental H/L values on the beach became much larger than theory for $H/L > 0.0279$.

During the course of a study on the sorting of beach sediments by shoaling waves [*Ippen* and *Eagleson*, 1955], it became necessary to determine accurately the local or transformed characteristics of the shoaling wave. In view of the shortcomings of existing knowledge, it was found desirable to measure these characteristics again.

Experimental equipment and procedures—The experiments were carried out in the 100-ft wave channel of the Hydrodynamics Laboratory at the Massachusetts Institute of Technology. The working section of the glass-sided channel is 30 in. wide, 36 in. deep and 90 ft long.

At one end of the channel a plane, false-bottom beach of 1/14.8 slope was installed occupying 36 ft of the working section. The surface was coated with a carefully graded angular sand of mean diameter, $k = 0.0060$ ft. Shallow-water waves were generated at the other end by means of a vertical faced piston which reciprocated horizontally and was controlled by a hydraulic servo-mechanism

TABLE 1—*Characteristics of test waves before transformation*

Wave	H	L	T	d	d/L	H/L	H_o/L_o (theoretical)	Approx. H_o/L_o
	ft	*ft*	*sec*	*ft*				
1	0.186	8.92	1.428	1.75	0.196	0.0209	0.0176	0.020
2	0.265	11.16	1.684	1.75	0.157	0.0237	0.0200	0.020
3	0.354	8.42	1.389	1.75	0.208	0.0420	0.0390	0.040
4	0.234	5.91	1.101	1.75	0.296	0.0396	0.0411	0.040
5	0.230	4.36	0.938	1.75	0.401	0.0528	0.0535	0.054
6	0.440	7.20	1.235	1.75	0.243	0.0611	0.0611	0.060
7	0.357	5.99	1.105	1.75	0.293	0.0598	0.0601	0.060

of continuously variable stroke and frequency. An expanded aluminum wave filter immediately following the generator removed secondary disturbances.

Wave characteristics were determined by capacitance-type profile wires in conjunction with a commercial recorder. Details of these components, together with calibration procedures, are given by *Ippen* and *Eagleson* [1955]. Two fixed gages were used in the constant-depth portion of the channel ten feet apart, the downstream gage being 10.5 ft from the beach toe. A movable gage with two wires one foot apart was used in shoaling water. The distance between the wires was large enough to permit satisfactory travel-time measurements and at the same time was short enough to keep the error due to linear interpolation to a minimum. Since the celerity is a non-linear, decreasing function of distance, the assumption of linear variation between the probes gives a celerity somewhat less than actually exists. Owing probably to the presence of reflected waves, the individual measurements of wave height varied ±4 pct from a mean curve drawn through them. Thus while one gage will suffice for height measurement, the height was interpolated linearly between gages.

The celerity of all waves whether stable or transforming was defined as the average speed of travel of the front and rear intersections of the wave profile and the still water surface. Characteristics of the seven test waves in the constant depth portion of the channel (that is, before transformation) are given in Table 1.

Transformation characteristics of Wave 7 were also obtained on bottom roughnesses $k = 0.0025$ ft and $k = 0$ ft. The only effect of roughness noted was a change in the position and thus characteristics of the breaker.

Presentation and Discussion of Results

Transformation of wave celerity or length—Local celerities of the transforming waves were computed at two-foot intervals along the sloping beach by (6) and (7) using the measured geometric characteristics.

As a check on the basic assumption of Rayleigh that waves of the same geometric characteristics have the same kinematic characteristics in water of the same depth whether the bottom is flat or gradually sloping, these local celerities were compared with the value determined by experiment. The results of this comparison may be seen in Figure 1.

Considering the fact that (7) neglects the effect of height, it is surprising to note the close agreement of theory and experiment over the full range of transformation. For most of the test waves the experimental celerity is slightly greater than theory early in the transformation, owing probably to neglect of height, but as the transformation

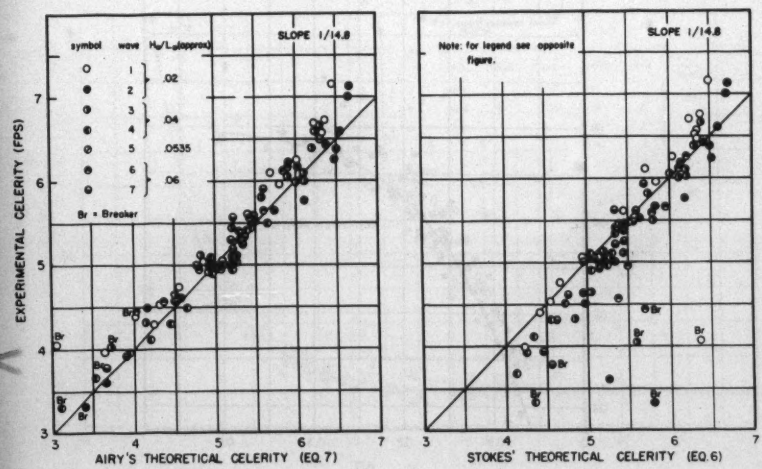

Fig. 1 – Transformation of celerity

progresses and the height increases (celerity decreases) the expected divergence of theory and experiment does not occur.

On the other hand, examining the correspondence between Stokes' finite amplitude theory (6) and experiment, a divergence is found in the latter stages of transformation. In the early stages of transformation where the wave profile is still 'Stokian' the height correction improves agreement, but as the wave deforms and departs from the theoretical in shape, the correction becomes too large. The implication is that the effect of shape on the local celerity of the transforming wave is opposite to that of height and that at least for the experimental conditions investigated is approximately equal thereto and independent of incident steepness.

Since the period of the transforming wave remains constant, Figure 1 shows the transformation of wavelength as well. In order to obtain a better picture of the position of each point in the transformation process, the wavelength data are plotted in Figure 2 against d/L, L_0 being determined from the period through (8). Data of *Wiegel* [1950] (obtained by scaling from enlargements of the figures in the author's paper and hence subject

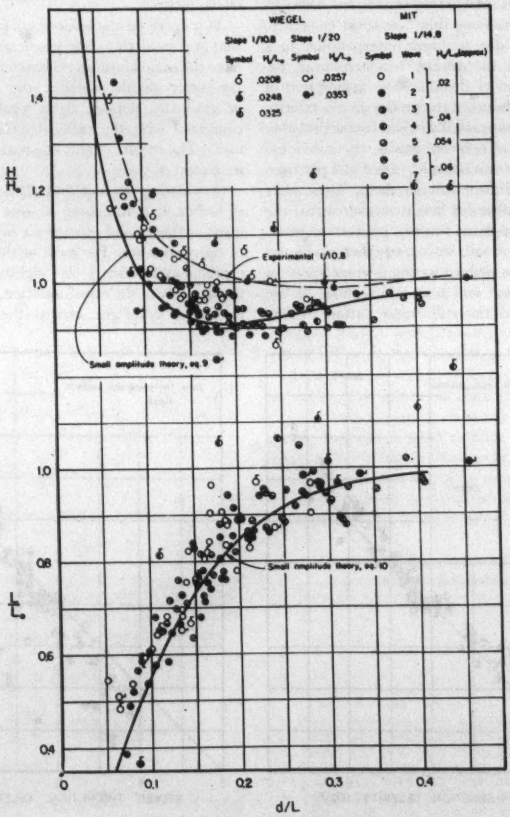

FIG. 2 – Transformation of wave height and length

to all errors inherent in such a process) for 1/10.8 and 1/20 slopes have been added to the figure and show the same trend mentioned above, that of slightly higher experimental than theoretical lengths over the entire range of transformation. However, no trend with slope is visible.

Transformation of wave height—Since the incident wave was in all cases a shallow-water wave, it was necessary to define an equivalent deep water wave in order to obtain H_0. Division of (9) by (10) yields an expression for transformation of steepness solely as a function of d/L

$$\frac{H}{L}\frac{L_0}{H_0} = \left[\frac{2\cosh^2\frac{2\pi d}{L}}{\frac{4\pi d}{L}+\sinh\frac{4\pi d}{L}}\right]^{\frac{1}{3}} \operatorname{cotanh}\frac{2\pi d}{L} \qquad (11)$$

Substitution of the incident values of H, d, and L in (11) defines an equivalent deep water steepness H_0/L_0. Multiplication of this steepness by the deep water wave length as defined by (8) yields the equivalent deep water wave height, H_0.

In Figure 2 wave-height-transformation data from all three slopes are plotted versus d/L in comparison with (9).

Considering for the time being only the data for the 1/14.8 slope because of their regularity, the experiment is seen to agree fairly well with theory up to the point of minimum height, shoreward of which it becomes divergently greater than the theory.

As can be seen from (5), any correction to the theoretical celerity for the effects of finite amplitude or to the height for the effects of viscosity merely serves to amplify the divergence. Reflections have been shown to be negligible for slopes less than 4.5° by *Caldwell* [1949].

Use of (2a) in place of (2b) in (4) corrects the theoretical height ratio by a maximum of +12 pct for the data presented. This correction is approximately 50 pct of that necessary for agreement with experiment and thus cannot be neglected, but it is the remaining error which is of primary interest here.

Explanation for this divergence probably lies in the inapplicability of the expression for nE, the amount of energy traveling with the wave. Assuming conservation of power, the quantity nE/H^2 is thus too large as given by even the finite amplitude theory. E/H^2 is essentially a shape parameter and thus will take on different values reflecting the changing asymmetry of the wave while n depends upon the energy partition. *Rayleigh* [1911], has shown the wave energy to be divided equally between kinetic and potential only for waves of small amplitude in constant depth. Both of these criteria are violated in the shoaling wave. Further experimental work is

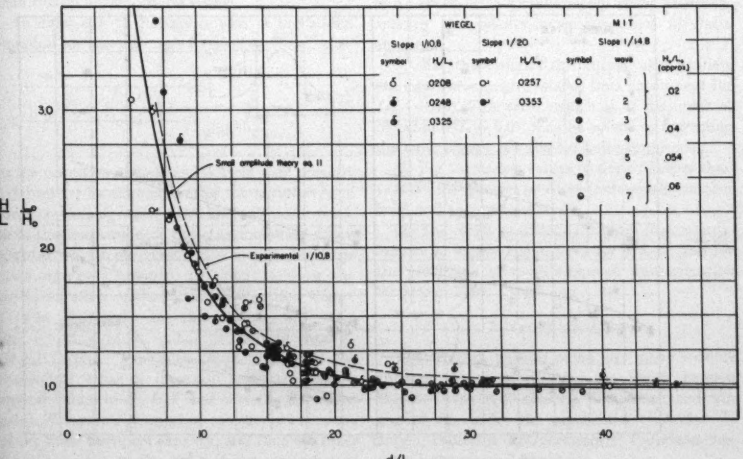

FIG. 3 – Transformation of wave steepness

needed to define the actual energy budget in a transforming wave.

It is again significant that the divergence commences at approximately the point of minimum height where the wave deformation becomes more pronounced and gets worse as the asymmetry increases.

Although the data for both the 1/20 and 1/10.8 slopes show scatter, mean curves show the same trend as that for the 1/14.8 slope, and show an effect of slope itself only for a slope of 1/10.8. This is again in agreement with the findings of *Caldwell* [1949] with respect to reflection.

The effect of increased slope (1/10.8) is to make the heights greater early in the transformation. In this stage, portions of the kinetic energy are added, through reflection, to a potential energy which is very little reduced from its deep water value. Later in the transformation, when reflections and repartition have reduced the quantity of available energy, the heights should be less than for flatter slopes at the same d/L.

Transformation of steepness—Eq. (11) was used with values of the experimental wave in the constant depth portion of the channel, to define an equivalent deep water wave. Thus in Figure 3 a comparison of the data with this equation gives a curve of relative steepness which has been forced into agreement with theory at the beginning of the transformation. The agreement for both the 1/20 and 1/14.8 beaches continues to be excellent up to breaking, with the slope effect showing up in slightly higher steepnesses for the 1/10.8 slope. This is due to the above-mentioned effect of slope on the height.

Asymmetry about the still water level—Because of the role played by asymmetry of the surface profile in determining the magnitude of the mass transport velocities, it is interesting to compare the experimental ratios of crest height to wave amplitude and crest length to half wave length with the corresponding ratios predicted by theory. Since mass transport is a 'second-order' effect the Stokes relationships for surface profile are used. The expression for crest height a_1 may be written

$$\frac{2a_1}{H} = 1 + \frac{3}{8}\pi \frac{H}{L} \frac{\sinh \dfrac{4\pi d}{L}}{\left(\sinh \dfrac{2\pi d}{L}\right)^4} \tag{12}$$

while, referring to Figure 4, the trough length may be given by

$$1 - \frac{L_c}{L} = \frac{\theta_1}{\pi} \tag{13}$$

where

$$\frac{2\cos^2\theta_1 - 1}{\cos\theta_1} = \frac{8}{3\pi}\frac{L}{H}\frac{\left(\sinh \dfrac{2\pi d}{L}\right)^4}{\sinh \dfrac{4\pi d}{L}} \tag{14}$$

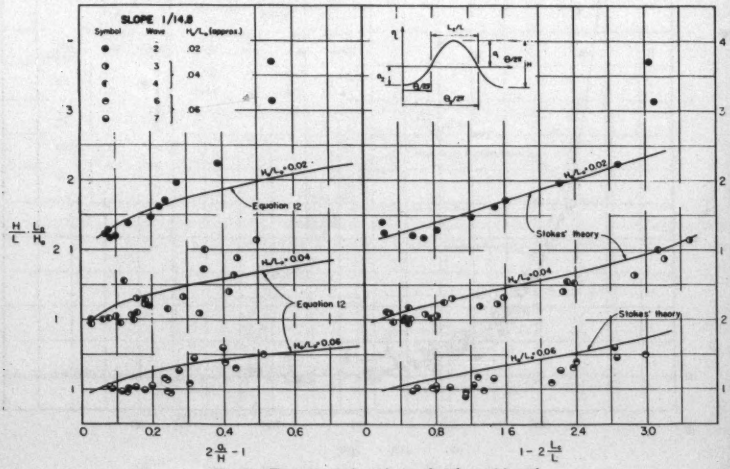

FIG. 4 – Transformation of crest height and length

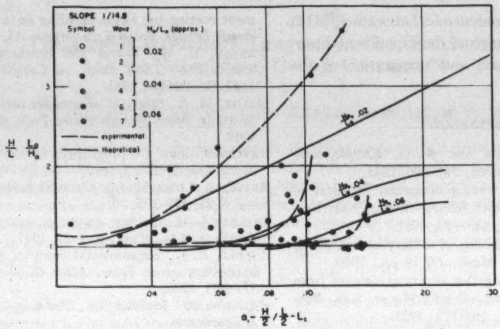

FIG. 5 – Asymmetry with respect to still water level

Figure 4 shows the asymmetry of height to be greater than Stokes predicts for relative steepnesses, $(H/L)(L_0/H_0)$, less than 1.5. Beyond this point the theoretical wave becomes divergently more asymmetrical. The asymmetry of length is also shown in Figure 4 and indicates the theory to predict a more symmetrical wave up to a relative steepness of about two. On the other hand, for $(H/L)(L_0/H_0) > 2$ the actual wave becomes divergently more symmetrical than the theory. The combined effect of these two asymmetries is to give a wave crest which is steeper than Stokes indicates early in the transformation and flatter than theory in the breaker region.

An indication of the applicability of the Stokes equation for mass transport velocity

$$\overline{U} = \tfrac{1}{2}\left(\pi\frac{H}{L}\right)^2 C \frac{\cosh\dfrac{4\pi(d-z)}{L}}{\sinh^2\dfrac{2\pi d}{L}} \qquad (15)$$

to the condition of a sloping bottom may possibly be obtained by examination of the asymmetry of the transforming wave about the still water level. It is the magnitude of these asymmetries which controls, to a large extent, the magnitude of the mass transport velocity. In order to show the combined effect of these two asymmetries, Figure 5 was prepared. In this figure the ratio $(a_1 - H/2)/(L/2 - L_c)$ is plotted against $(H/L)(L_0/H_0)$. The solid lines represent the theoretical value of the ratio using the experimental values of H, L, T and d at the particular point. This parameter may be considered a measure of the mass transport velocity, and thus wherever the theory lies to the right of the experimental curve the indication is that the theory predicts too large a mass transport velocity. In general, for waves of high steepness, Figure 5 indicates the mass transport velocities as given by (15) to be too large early in the transformation and near the breaker, while at intermediate values of the relative wave steepness, $(H/L)(L_0/H_0)$, it is too low.

CONCLUSIONS

(1) For slopes 1/10.8, 1/14.8 and 1/20, the small amplitude theory of Airy is satisfactory for the prediction of celerity of the transforming wave up to the point of breaking. This agreement is a result of an effect of wave asymmetry which evidently opposes the celerity-increasing effect of finite amplitude.

(2) For these slopes this theory also predicts the local wave height smaller than experiment for $d/L < 0.2$. This error, which is of the order of 25 pct at $d/L = 0.07$, may be halved by correcting the basic energy relation for finite amplitude.

(3) For increasing values of slope (steeper than 1/14.8) the theory predicts increasingly smaller heights than experiment.

(4) The small amplitude theory of Airy is satisfactory to within about 3 pct for $d/L > 0.10$ for the prediction of wave steepness transformation for slopes 1/20, 1/14.8 and 1/10.

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Particular credit is due Luis A. Peralta, Research

Assistant at the Hydrodynamics Laboratory, MIT, for performance of much of the experimental program, analysis of data and preparation of the figures.

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The Use of Parachute Drogues in the Measurement of Subsurface Ocean Currents*

GORDON VOLKMANN, JOHN KNAUSS, AND ALLYN VINE

Abstract—A technique for the measurement of subsurface currents is described in which a standard parachute is used at depth as a sea anchor for a small surface float. By tracing a series of drogues set at various depths, a current profile may be obtained. Hydrodynamic corrections (amounting to about ten per cent of the shear) have been computed and other refinements incorporated which make this a feasible method for measuring the main structure of the major ocean currents down to depths where the current is five to ten per cent that of the surface current.

Introduction—There have been few measurements of subsurface currents in the open ocean, as indicated by *Bowden* [1954] in his survey of the literature. On the other hand there is no shortage of papers describing current-measuring devices. *Böhnecke* [1954] listed some half a hundred different instruments and ended by quoting *Fleming* [1952] who suggested that what was needed were fewer new instruments and more measurements. The present technique has been developed over a period of three cruises in three years, and has been used for a relatively large number of subsurface current observations by ourselves and others, the results of which will be published in the future. Like other methods it has certain limitations, but it is a cheap and easy technique which has been successfully used.

The method is that of the free-floating drogue which is one of the oldest, having been used by the *Challenger* Expedition, 1873–1876 [*Thomson* and *Murray*, 1885, p. 79]. It also appears to be one of the least used, since in Bowden's summary of subsurface-current observations in deep water, all measurements were made with propeller-type instruments. However, the drogue technique has been used in recent years by *Stommel* [1954] and by *Cromwell* and others [1954].

In brief the drogue system consists of a standard aviator's parachute suspended by a weighted wire from a surface float (Fig. 1). The ideal subsurface drogue is one in which the ratio of drogue surface area to float and wire surface area is infinitely large since, as described below, a correction must be applied to the trajectory of the drogue system based on the drag of these appendages. In this respect the recent work of *Swallow* [1955], who has devised a neutrally buoyant drogue with no surface float, is the ideal. Our drogue system was designed with three points in mind. (1) The drag of the wire and surface floats should be small compared to the drag of the sea anchor. (2) The parachute must be given every chance to open and to remain open under water, and the other components and the techniques should be reliable enough so that they could be used with a high percentage of successes. When possible, positive identification of a proper or malfunctioning drogue should be provided. (3) The drogue system should be cheap enough to be considered expendable.

The work reported on was started by Vine, in March and April 1951, on R/V *Atlantis* in the Cayman Sea and continued in April 1953 on R/V *Spencer F. Baird* off Southern California and on EASTROPIC in October to December 1955 on R/V *Horizon* and *Spencer F. Baird*.

Parachute—The standard flat circular aviators' parachutes used as drogues were obtained from the armed forces over-age supply. They are also available on the civilian surplus market, although care should be taken with the latter source because parachutes are sometimes sold without shrouds to prevent re-use. The parachutes used have an effective cross section of 200 sq ft when completely open, and they are almost weightless in water, making it possible to use a relatively small surface float. Furthermore they can be launched unopened (our technique was to stuff them into large mailing tubes and 'pour' them over the side). The problem of launching an already opened or rigid frame-work type of drogue of similar cross section is formidable.

Very few pounds of force are required to open a parachute in the air, and once open it stays open. The same appears to be true when parachutes are used as deep-sea drogues. To check this, parachutes were observed underwater by SCUBA-equipped divers. The only difficulty was the tendency for the

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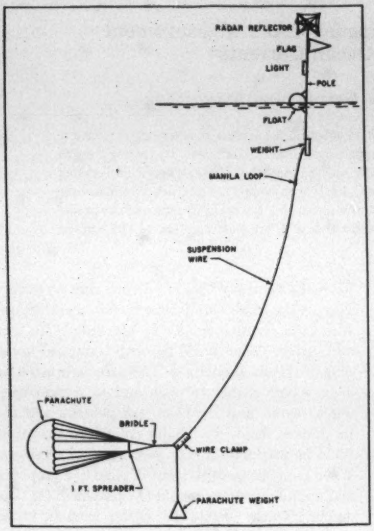

FIG. 1 – The parachute drogue system

shrouds to twist before the parachute opened as it fell through the water. In the tests conducted the parachute never failed to open, but the opening time was delayed by twisting, and a greater initial force was required. This difficulty was alleviated by inserting a spreader bar between the two groups of shrouds. Any twisting was taken up by the line which ran from the spreader bar to the wire (Fig. 1).

Wire and rigging—The suspension wire used was 0.030- or 0.040-in music wire, and while it has definite disadvantages, it was satisfactory for these purposes. The disadvantages are that it kinks easily, and, when it does, it only has about 20 pct of its original strength. It also corrodes quickly, as may be seen from the fact that 0.030-in wire generally parted after 24 hr with about a 30-lb pull on it. The advantages are that it is cheap, light, non-twisting under tension, and available in long lengths. If a laid wire is used, a good ball bearing swivel at the parachute end is recommended. The wire was in our instance the limiting factor in the length of life of the drogue, which was 24 to 36 hr. The use of either heavier wire or galvanized wire would lengthen this life considerably.

Since there is no need to reel in on this type of rig, a simple spindle and brake suffice as a winch. On two of the three cruises the front axle of an automobile complete with brake was used with great success. On the last cruise the music wire was supplied on wheel rims purchased to fit the automobile axle. The addition of small plywood flanges to prevent the wire from slipping off this drum makes a cheap and effective rig. The purchase of wire on drums rather than coils is strongly recommended because rewinding from coils requires special equipment and is lengthy and tedious.

A few of the many methods of holding music wire are shown in Figure 2. The cheek clamp is the strongest and most convenient, since it can be applied while the wire is under tension. It can also be clamped quickly, an asset when wire tension is high and mounting rapidly.

To ease the strain on the wire during drogue launching, the surface buoy with wire attached was put over first. The ship then steamed away until the proper amount of wire was out and then stopped while the parachute was 'poured.' This eliminated any tendency to sea-anchor the ship on 0.040-in music wire to an open parachute. Since music wire has a tendency to fatigue when bent on a short radius, manila leaders were used whenever practicable. Manila, marline, and friction tape were used copiously to prevent chafing and to lash the components together.

Floats—A different type of float was used on each of the three cruises: extra strong meteorological balloons in gunny sacks, canvas-covered balsa wood floats (Navy dan-buoys), and 14-inch Japanese glass fishing floats. The balloons are the cheapest and easiest to stow but are the least durable. The

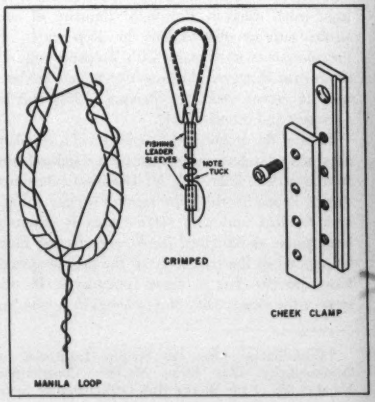

FIG. 2 – Various techniques for securing music wire

fishing floats proved the most satisfactory, but the storage of a hundred or more glass floats on a small ship can be a problem. Usually a single glass float provided enough buoyancy. The float was lashed to a bamboo pole, to the top of which were attached flags, a light, and a radar reflector. The suspension wire was attached to the bottom of the pole, and it was necessary for the parachute with its attached 20-lb weight to sink to its full depth before the pole would stand completely upright. The pole was so weighted that before the addition of the 20-lb load, it would lie at an angle of about 30° with the surface. Thus one could tell when the drogue system was properly set by watching the pole swing to an upright position, and one could also tell when something was amiss (usually a parted wire) when the pole flopped down. This type of positive identification of the fact that the drogue was properly set or that it had broken loose saved considerable time on the most recent cruise.

It can take as long as an hour for a parachute drogue and 20-lb attached weight to sink to 200 m. To eliminate the long time required for an open parachute to sink to the greater depths, additional weights were secured by means of a simple time release to the apex of the chute, which then descended closed. Here as a signalling device an additional float was attached between the upper end of the wire and the surface buoy. When the parachute was at depth, this float would be submerged under the additional weight of the release weights, but it would reappear when these weights were released. Also, when something parted, this second float would pop high out of the water and thus give a positive signal that something was amiss.

Measurement techniques—Currents at various depths were measured by tracing the movements of the various floats. Of the two general ways in which this can be done, neither is completely satisfactory: one is to measure the movement of the drogue over the surface by standard navigational techniques, that is, celestial fixes or Loran; the second is to measure the movement relative to some reference point, that is, an anchored ship, buoy, or some other easily observable reference.

The conditions were different on each of the three cruises and different techniques were used to solve this problem. Loran coverage was inadequate in each area as it is over most of the oceans of the world, and celestial navigation has certain obvious limitations with respect to accuracy, time between fixes, and the uncertainties of cloud formation. In the Cayman Sea, where we were often within sight of land, piloting techniques were used. When land fixes were not available the same surface-float, piano-wire rig was attached to an anchor and used as a reference buoy. The circular area of possible positions created by the necessary scope (we used a wire-length to water-depth ratio of 1.1 to 1) is reduced to a segment of a circle by a steady current, and this uncertainty can be considerably reduced by time averaging.

During the 1953 cruise of the *Spencer F. Baird* off Lower California where the currents were weak a slightly heavier version of the anchored buoy was used, and celestial navigation was employed to check possible lifting or dragging of the anchor.

On the EASTROPIC Expedition into the eastern part of the Equatorial Current and Countercurrent system a parachute drogue at 2000 m was used as the reference buoy. In this area of strong currents, it was felt that any slight drift of the water at 2000 m could be tolerated. An upper limit of this drift was established by celestial fixes but was never found to be more than predicted (see next section) and may have been less.

The range and bearing from the reference point to the other drogues was measured by one of three methods: (1) By timing the vessel up and down current along an average fixed course, taking bow and beam bearings or angles of depression from the horizon to establish the distance of the buoys from this course. (2) By timing the vessel from the reference buoy to each buoy and return, along a course parallel to the visual bearing between the two. (3) By standing by the reference-buoy and measuring range and bearing by radar.

The last method is, of course, the most efficient and the most accurate. Unfortunately the radar was not working properly on any of the three ships used by the authors. (EASTROPIC was a two-ship cruise and radar was used by Townsend Cromwell on the other vessel to great advantage.)

Corrections to observations—Since the velocity of the surface water is in general different from that of the water at the depth of the parachute, there is a flow of water past the surface buoy. This implies a slower flow of water by the parachute, since there must be a balance of the horizontal forces on the drogue system. These horizontal forces are given by

$$F = \tfrac{1}{2}\rho C_D A V^2 \qquad (1)$$

where F is the force, C_D a non-dimensional drag coefficient, ρ the density of the fluid, A the cross sectional area, and V the relative velocity of the fluid.

(The equation for the horizontal force created by a sinusoidal motion, for example, surface waves, of

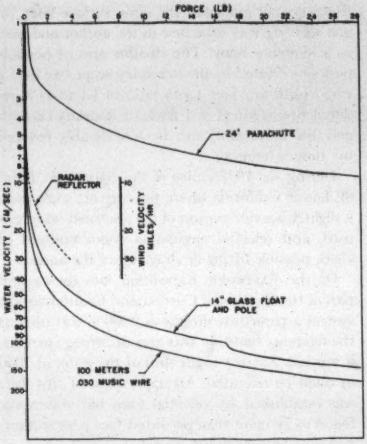

FIG. 3 – Drag forces on various components of the drogue system (note different scale for radar reflector in air)

orbital velocity U superimposed on a steady current V and integrated over one cycle is $F = (\frac{1}{4})\,\rho\, C_D A\,(V^2 + U^2/2)$. For the shallower depths the parachute may be within the region of wave motion and complicate the picture phase-wise. For the greater depths it is not clear how much of the oscillatory force is transmitted down the wire to the parachute.)

Figure 3 has a plot of force as a function of speed through the water for a 24-ft circular flat parachute computed from (1). The area of such a parachute is 200 sq ft. (The diameter must be reduced by a third in calculating the area of the parachute, according to the USAF *Parachute Handbook*, 1951.) The drag coefficient was assumed to be 1.5, although this may be subject to some error. The coefficient is a function of the porosity of the material as well as the geometry. For a completely imporous chute, it is 1.7; for a standard chute in air it is 1.3 [*Heinrich*, 1954]. The porosity of the parachute material is less for sea water than for air, but no measurements have been made of its effect on the drag coefficient.

Also plotted in Figure 3 are the forces at different speeds computed for a surface float consisting of a 14-in float and 8 ft of bamboo pole, both submerged, 100 m of 0.030-in music wire, and a two-ft Navy lifeboat radar reflector in air. The curves for the float and wire were calculated using the appropriate drag coefficients in *Rouse* [1946]; the curve for the radar reflector (type MX-138/A) is based upon measured values of drag.

To calculate completely the forces on the parachute and hence the speed at which it moves through the water, it is necessary to know exactly the forces on the float and wire. This is in general not possible, nor in many cases is it necessary if the ratio of drogue to float area is large enough. From Figure 3 one can see that a current which flows at 50 cm/sec to a depth of 100 m will drag a parachute at 200 m through the water at about 4.5 cm/sec, assuming no current at 200 m. It has been our experience that a first-order correction such as this will correct the measurements to a couple of centimeters per second and that both the uncertanties in observation as well as short-period changes in the current make it impracticable to try to reduce the error any more.

The standard flat parachute is unstable. As it falls through the air it falls at an angle of about 22° with the vertical. This angle of stability is again a function of the porosity of the chute and is 45° for a completely imporous parachute [*Heinrich*, 1954]. Hence the direction of the 4.5 cm/sec correction of the previous example could be as much as 22° to 45° in error. It is believed, however, that this directional correction is negligible. In the first place an uncertainty of even 45° on a 5 cm/sec correction to a 50 cm/sec current does not change the resultant by more than ±4°. Secondly, underwater observations of parachutes used as drogues indicate that if there is a directional preference for the towed parachute it is in the downward direction.

The actual depth of the parachute drogue can be estimated by assuming the wire to be a rigid member and the forces in equilibrium (hence the depth of the 200-m drogue with a 20-lb weight and pulled by a 6-lb force would be $d = 200 \cos\phi$ where $\phi = \tan^{-1} 6/20$ so that $d = 191$ m), or by the more rigorous method of *Pode* [1951], where the forces on the flexible wire are also considered. In this example, assuming 0.030-in wire, the calculated depth is 189 m. As long as ϕ is a relatively small angle the two methods give about the same results.

Discussions and conclusions—The techniques and equipment described have been used successfully in the measurement of surface and subsurface ocean currents in both the Atlantic and the Pacific. On EASTROPIC, continual tracking of as many as five drogues at various depths with reference to the 2000-m drogue was done by radar, and up to four drogues were tracked at once by continuously running between them and the reference drogue. It was

nearly always possible to get a satisfactory picture of the vertical current structure down to several hundred m during the daylight hours.

The shear measured in these cruises was nearly always between 10 and 100 cm/sec. The little experience we had in three-knot (150 cm/sec) shear indicated that perhaps the drogue system would have to be sturdier to be used in the Kuroshio or the Gulf Stream.

It seems clear from the force computations in Figure 3 that in areas of even modest surface currents the correction which must be applied due to shear may easily exceed the velocities which other workers have shown to exist at greater depths. This suggests that the usefulness of this technique may be limited to depths where the current is more than 5 to 10 pct that of the surface current.

However, for the task of measuring the structure of the major ocean currents where an error of a few centimeters per second can be accepted, it is believed that the technique as described is a useful one.

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Effect of Various Hydroclimatic Factors on Snowmelt Runoff

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Abstract—The influence of various climatic factors on snowmelt runoff was determined through 583 multiple correlations for streams in a Bureau of Reclamation multiple-purpose reservoir system located in northern Colorado and southeastern Wyoming. The use of high-speed electronic computers facilitated the solution of the equations and the determination of various statistical parameters considered indicative of accuracy. The superiority of using both precipitation and snow-survey data as primary factors was indicated. Other factors, including winter and spring temperature and melt-season precipitation, were found helpful in individual cases, but not uniformly. Investigations of factors antecedent to the snow-accumulation period revealed no significant increase in accuracy. Numerous investigations were also made of different methods of weighting the primary factors.

Numerous professional papers have been published on the subject of forecasting snowmelt runoff. It would be impractical to review all the previous work on the subject or even to present a full bibliography on the subject. This paper does not present methods of analysis that could be considered new. However, it does record the results of an exceptionally large number of analyses on a limited number of forecast points, affording consideration of a variety of factors in a number of different forms. In this respect the studies may have been unusual and the results worthy of presentation.

Drainage Basin Characteristics

The Bureau of Reclamation multiple-purpose reservoir system for which forecasting procedures were developed is shown on Figure 1. The watersheds are in three basins, the Upper Colorado, North Platte, and South Platte Basins. Data on the watersheds are listed in Table 1.

The vegetal covering in the watersheds varies with the altitude. Above timberline, around 12,000 ft, the cover is scanty and consists of tundra and alpine-type vegetation. Below timberline to about 8000 ft elevation, the mountain slopes are heavily timbered with spruce, fir, ponderosa pine and aspen. Below about 8000 ft the slopes are generally less heavily wooded, with sagebrush and scattered grasses at the lower altitudes and in the rolling areas.

Snow does not ordinarily accumulate in substantial quantities during the winter below about 8500 ft. Average annual precipitation varies from about nine inches per year in the lower elevations to over 50 inches around the highest peaks.

Procedures for Selecting Forecasting Methods

Variations in seasonal water supply, although closely related to annual variations in accumulated moisture in the form of snow on the watershed, can be influenced by a number of factors which contribute to the variability in the water yield. The need in a forecasting equation, therefore, is for an expression of the combined effect of the several factors influencing seasonal runoff. An expression of the following type was used in the studies

$$Y = a + b_2X_2 + b_3X_3 \cdots b_nX_n$$

where

Y = expected seasonal runoff (dependent variable)
X's = variable factors influencing runoff (independent variables)
b's = partial regression coefficients
a = constant term

For each equation, values were computed for the coefficient of multiple correlation, $\bar{R}$ (adjusted for length of record and numbers of constants), standard error of estimate, $\bar{S}$ (adjusted), and the standard errors of the b coefficients. The derivation of the above equation and of the measures of reliability were based on multiple correlation. [*Ezekiel*, 1942]. A detailed discussion of multiple correlation methods in forecasting is described by [*Ford*, 1953].

Because of the number of possible factors influencing runoff and the variety of ways in which the data may be grouped and weighted, numerous trial correlations, involving factors which could logically be expected to affect runoff, were required to enable the selection of the most de-

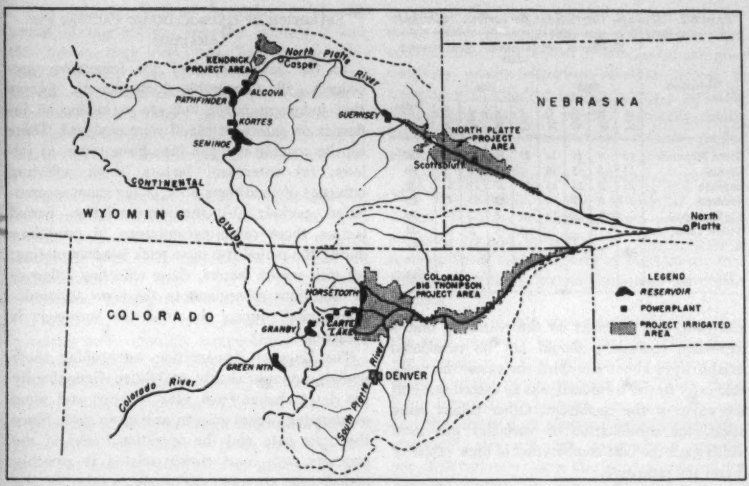

FIG. 1 – Map of operational area

sirable forecasting equation. Needless to say, a study of this magnitude would involve many man-hours of labor if computations were carried out manually. Computations for the studies were made on a high-speed electronic computer which reduced the time required to complete the analyses and effected great economies over manual methods. While the use of machine methods is not new, the results of these studies furnished further evidence that such methods allow analyses to be made that would otherwise be impractical.

Computations by the machine included the determination of the partial regression coefficients, the constant term, the coefficient of multiple correlation, the standard error of estimate, and the standard errors of the partial regression coefficients, for each of the trial correlations. Also, the covariance matrix was evaluated to facilitate any desired changes of variables. For the 1953 and 1954 forecasts, some 583 multiple correlations were computed, as shown in Table 2.

The selection of the forecasting equation was guided primarily by the parameters mentioned previously. Because of the comparatively short period of record (generally 15 to 18 years), the number of terms in the equation was kept to a practicable minimum, since an increase of one in number of variables is equivalent to reducing the period of record by one year, as far as statistical reliability is concerned. A regression coefficient, b, was considered significant if its standard error, σ_b, was equal to or less than $b/2$. This point cannot be precisely defined and was selected somewhat

TABLE 1 – *Watersheds studied for forecast procedures*

Point of runoff measurement	Drainage area	Elevation range	Normal annual runoff
	sq mi	ft	ac ft
North Platte River inflow to Seminoe Reservoir, Wyo.	7340	6400–13,000	1,070,000
Colorado River inflow to Grandy Reservoir, Colo.	311	8300–14,300	265,000
Willow Creek inflow to Willow Creek Reservoir, Colo.	127	8100–12,400	55,000
Blue River inflow to Green Mountain Reservoir, Colo.	599	8000–14,000	405,000
St. Vrain River near Lyons, Colo.	226	5300–14,300	95,000
Big Thompson River at Estes Park, Colo.	151	7500–14,300	93,000
Cache la Poudre River near Ft. Collins, Colo.	1048	5300–13,600	300,000

TABLE 2 – *Multiple correlations for various watersheds*

Watershed	Number of correlations for given forecast date								Total
	1953				1954				
	Feb.	Mar.	Apr.	May	Feb.	Mar.	Apr.	May	
Green Mountain	15	9	14	14	25	20	20	19	136
Grangy	13	8	18	16	7	10	9	9	90
Seminoe	21	8	14	13	15	27	27	13	138
Poudre	...	6	11	9	...	12	12	12	62
Big Thompson	...	9	9	12	6	8	7	7	58
Willow Creek	...	...	...	...	6	14	8	10	38
St. Vrain	...	...	...	...	...	12	33	16	61
Total									583

arbitrarily but is based on the reasoning that a regression coefficient should not be considered reliable if, in about one-third the cases, the probable error in the coefficient was to exceed one-half the value of the coefficient. Other things being equal, the combination of variables was used which gave the best combination of high values of $\bar{R}$ and the ratio σ_b/b.

The final selection of the forecasting equation did not, however, become a mechanical process of choosing the combination that had merely the best statistical indices of accuracy. The equation selected was also subjected to the test of logical judgment. For example, equations were not adopted if certain b values were opposite in sign to that which would logically be expected, such as a negative b coefficient for spring precipitation. Statistical accuracy was sacrificed if an equation having lower $\bar{R}$ and higher σ_b/b included variables which were believed to give enough better basin coverage to justify bypassing an equation of higher statistical accuracy but poorer coverage. In other cases, a mechanical processing of data yielded results which gave undue weight to one variable, leaving insignificant weight to another variable that experience and judgment had shown to be highly pertinent. In these cases, even though statistical accuracy was apparently good, sound judgment dictated that such equations not be selected.

High correlation between independent variables may result in an apparent lack of consistency. Where such a relationship existed, the variables were combined when practicable into a single independent variable. Other manifestations of interaction between variables were indicated by an increase in the significance of a particular factor in the presence of a supplementary factor.

SELECTION OF HYDROCLIMATIC FACTORS FOR ANALYSIS

In the development of the forecasting procedures, all measurable hydroclimatic factors that judgment might indicate as having an influence on snowmelt runoff were analyzed. These can be roughly grouped into three types, as follows: (a) antecedent factors, those reflecting influence of conditions prior to the snow accumulation period; (b) snow-accumulation period factors, those reflecting influence of conditions during the period the snow pack is accumulating; (c) melt-season factors, those reflecting influence of conditions subsequent to the snow accumulation period, during the time the snowmelt is occurring.

The lines of demarcation establishing these periods cannot be clearly established. Undoubtedly the dates change from year to year, and some overlapping occurs even in any given year. Since the basic data and the operational uses of the forecasts were most closely related to monthly periods, no attempt was made to identify the periods closer than to full monthly increments. A precise delineation of these periods is not essential, since any minor errors that exist in the assumed length of period will be largely compensated in the mechanics of the correlations.

The snow-accumulation period was assumed to start on October 1, on the basis of visual observations and general knowledge of the time at which the snows begin to be retained for winter storage in the snowpack. The snow-accumulation period was assumed to end on either March 31 or April 30, the date having the greatest water content in the snow pack being selected as the end of the period. The snowmelt runoff season was assumed to be April 1 through July 31. This period was selected primarily from inspection of runoff records. Admittedly, some snowmelt runoff occurs during August and September; however, the amount is small with respect to the April–July flow. In addition, the purpose of most of the forecasts is to assist in reservoir operations, and since the streamflow has generally decreased by late July to an amount less than reservoir releases, the July 31 cutoff date will include the critical filling period of the reservoirs. The hydroclimatic factors selected for analysis follow.

Antecedent factors.

July through September precipitation.

October through December streamflow.

Snow-accumulation-period factors.

Precipitation: Various breakdowns of the precipitation occurring between October 1 and the forecast date were used. For example, the April 1 forecast trials could include the following periods of precipitation: (a) October–March; (b) October–December; (c) October–January; (d) October–December combined with January–March; and (e) October–January combined with February–March.

Snow-water content: various breakdowns of water content were analyzed, such as: (a) April 1 water content; and (b) February 1 water content combined with February–March increase in water content.

Combined snow-precipitation factor.

Temperature: The 1953 studies were made assuming mean monthly temperatures would be representative of the temperature excess. The 1954 studies were made assuming the temperature excess would be represented by the cumulative degree-days of daily maximum temperature over a given period and above a given base temperature. The base temperature was selected as that believed to be representative of the temperature at the average snow elevation at which melting would begin. The various measures of temperature that were investigated included: (a) September–November average temperature; (b) November–December temperature excess; (c) October–December temperature excess; (d) January–March temperature excess; (e) November–March temperature excess; (f) February average temperature; (g) March average temperature; and (h) February–March average temperature.

Melt-season factors.

Precipitation: The periods of precipitation investigated included: (a) April–June; (b) May–June; (c) April–July; (d) May–July; (e) June–July; (f) May; (g) June; and (h) July.

Temperature (April average).

Results of Analysis of Individual Factors

The following discussions reflect the results obtained in the analysis of the various factors. Due to the interaction of the various factors that might influence runoff, it is not possible to isolate the effect of one of the factors by simple correlation between that factor and runoff. Therefore, the effect was analyzed by multiple correlation, involving the factor under investigation in connection with one or more other factors known to have an influence on runoff. This approach does not establish conclusive results in a single test, because if the factors selected for test with the factor under investigation are not the best that could be used, the process of interaction can give deceiving results. However, if this process is repeated with different factors having a probable influence, a pattern of effect is generally established which can lead to fairly definite conclusions.

Varied combinations of precipitation stations—This was investigated most intensively in the Green Mountain watershed. Four precipitation stations, varying in period of record, altitude, and location in the basin, were usable. Comparisons were made with various combinations of the four stations.

The result of one comparison between use of the most centrally located station (Dillon) and the average of Dillon with another station indicated a moderate superiority for Dillon only. Four comparisons between use of Dillon only and the use of four stations indicated identical statistical accuracy. Six comparisons between use of two-station, three-station, and four-station averages indicated a very slight superiority for the three-station average.

The slight increase in statistical accuracy by use of a smaller number of stations did not appear to offset the additional value of obtaining more sampling points by use of all four stations. The increase in number of stations used would tend to minimize any observational error or abnormal storm distribution that might affect the precipitation measurement at a given single station. On the basis of the above analysis, it was concluded that for all basins in the Upper Platte system it would be advisable to use as many precipitation stations as possible, unless there was definite evidence of the unreliability of a particular station.

On the Poudre River, the value of a precipitation station high in the watershed, as compared with a station at low elevations, was clearly demonstrated. Correlations using records of Fort Collins, located on the plains at about 5000 ft elevation, were first attempted. When poor results were obtained, a partially correlated record was developed for Red Feather Lakes (elev. 8227), using nearby precipitation stations for correlation purposes to extend the relatively short periods of record for Red Feather Lakes. Multiple correlations using records of Red Feather Lakes increased the statistical accuracy from $\bar{R} = 0.27$ to $\bar{R} = 0.63$ for the March 1 forecast, and from 0.46 to 0.72 for the April 1 forecast. While the results

TABLE 3 – *Comparison of correlations with and without antecedent precipitation* (X_3)

Item	Feb. 1 forecast	March 1 forecast	April 1 forecast	May 1 forecast
Number of trials better with X_3	0	0	0	0
Number of trials about equal	0	1	4	2
Number of trials better without X_3	11	18	16	17

with Red Feather Lakes data were still not of desirable accuracy, the increase in accuracy over use of Fort Collins data was considered quite significant.

Varied combinations of snow courses—Variations in number, location, and methods of weighting snow courses were tried in practically all basins.

It was found that a limited number of stations could generally be selected which would give a slight increase in statistical accuracy over that obtained when all available courses in the basin were used. This was true in two trials for Green Mountain, one for Seminoe, and one for Granby. In no case was the increase in accuracy large enough to be significant, even though use of the larger number of courses generally required use of a record for some courses that was partially based on correlation with other snow courses. In one trial for the Poudre and one for Granby, the opposite result was noted, with greater accuracy for the larger number of stations. It was therefore concluded that all available courses should be used, in order to increase sampling points, and to reduce effect of observational error or abnormal snow accumulation at one course.

The use of different methods of weighting snow courses, in five trials for Granby and two for the Big Thompson, failed to give any appreciable difference in results. In one trial each for Granby and Green Mountain, individual courses or groups of courses were analyzed as separate variables. The results verified the theory that multiple correlations will not yield physically logical regression coefficients for interdependent variables. Negative coefficients and poor σ_b/b ratios resulted in these correlations, even though the individual variables yielded a high degree of correlation when simple correlations were developed. A significant increase in accuracy resulted for the watershed above Seminoe Reservoir when the snow courses were weighted in accordance with the proportion of seasonal runoff originating in the area represented by the course. It was concluded that unequal weighting of snow courses is not justified for small, relatively homogeneous basins, but that a weighting procedure is justified for large basins with wide variation in runoff characteristics, such as the watershed above Seminoe Reservoir.

Other investigators have suggested that the relation between supply, in terms of precipitation or snow water content, and runoff may not be linear, since in high runoff years the percentage of loss could differ from that in low runoff years. Therefore, a curvilinear relationship between runoff and snow water content was attempted in nine correlations for five basins in development of the May 1953 procedure. In these trials the values of snow water content, taken to powers of 1.5 and 2.0, were individually correlated with runoff. The results indicated no significant change in statistical accuracy from that found in a linear relationship. Use of such exponents would rapidly increase estimates of runoff with relation to snow water content, and, if an error existed in the relation adapted, the error would be magnified in the extrapolated range of the relationship. In the absence of evidence that a curvilinear relation was more fitting, a linear relationship was adopted. The writers believe that with data currently available, dependence upon linear relations is a more practical and generally reliable practice.

Antecedent factors—The July–September precipitation was investigated for six watersheds in the development of all 1954 forecasts. The results of the 68 comparisons, given in Table 3, indicate quite clearly that, within the limit of available records, the antecedent July–September precipitation is not a satisfactory expression of the effect of antecedent conditions on subsequent runoff.

The fall and winter streamflow (October through December flow except for one trial when the October–January period was used) was investigated for four watersheds in the development of the 1954 forecasts. In all of the five multiple correlations made with this factor the $\bar{R}$ was not increased significantly when fall and winter streamflow was used. While the number of correlations is somewhat limited, the results indicate that fall and winter streamflow is not a satisfactory expression of the effect of antecedent conditions on subsequent runoff.

While the use of antecedent factors yielded no significant improvement of the correlations, the weight of judgment is in favor of some such influence. The effect may be relatively small; how-

TABLE 4 – *Comparison of correlations using all or part of winter precipitation*

Item	March 1 forecast	April 1 forecast	May 1 forecast
Number of trials method A is better	0	1	6
Number of trials about equal	3	5	2
Number of trials method B is better	4	3	2

ever, the writers are not convinced that some such effect does not exist. Three explanations appear possible. Inaccuracies in the primary factors may obscure the effect, the historic experience may not include years of sufficient extreme in the antecedent factors to yield significant results, or the index chosen for antecedent effect may not be proper.

Snow accumulation period factors—The effect of various breakdowns of winter precipitations was tested for all basins, on the assumption that the effect of early precipitation would differ from that of later precipitation. Dividing times of December 31 and January 31 were tried for the breakdown into periods. Of six trials where a direct comparison was available, a slight advantage for the December 31 date was demonstrated in all but one.

A total of 26 comparisons was made between multiple correlations with October–December precipitation and January-forecast date precipitation (method A) and correlations with October–December precipitation only (method B). The comparison is shown in Table 4. The multiple correlations were made using snow water content as an additional variable. Thus, when both October–December and January-forecast date precipitation were used, the correlation included factors which are interdependent, to some degree; that is, the latter factor is correlated to some degree with snow-survey data on the forecast date. The inferiority of this combination in most cases was demonstrated by poor σ_b/b ratios, as would be expected when interdependent factors are used. It is interesting to note that use of total seasonal precipitation, when used in combination with snow data, appears less desirable for the early forecasts than for the late forecasts. This would indicate that the total seasonal precipitation for the late forecasts is less interrelated to snow water content than for the earlier ones.

The general conclusion to be drawn is that the best dividing time for considering winter precipitation is December 31. In multiple correlations involving snow water content, total seasonal precipitation should not be used for the early forecasts, but should be used for the May 1, and, in some cases, for the April 1 forecast.

Regarding the much debated point as to whether early or late winter precipitation is more effective in producing runoff, the results of the correlations were not conclusive. For the four correlations for Willow Creek and Granby that had a high statistical accuracy, the effect of October–December precipitation (as indicated by its b coefficient) was almost identical to that of the January-forecast date precipitation. For three correlations for Seminoe and Green Mountain, where only fair statistical accuracy was obtained, the effect of October–December precipitation was about twice that of the January-forecast date precipitation. On the other hand, for three correlations on the Poudre and St. Vrain, also involving only fair accuracy, the October–December was only about 60 pct as effective as the later precipitation.

Use of precipitation only—To verify the assumption that both snow-survey data and precipitation data should be used in development of forecast procedures, a limited number of comparisons were made of the use of precipitation data only with the use of both types of data. The results, given in Table 5, appear to substantiate previous opinions. Although statistical accuracy for the early forecasts may not always be improved by using both types of data, the increased sampling would justify use of both types. The increased general statistical accuracy and better sampling for late forecasts clearly indicates the desirability of using both types of data.

Breakdown of snow water content into periods—A limited number of analyses were made to determine whether the snow accumulation could be advantageously broken down by periods. These analyses were made by using the February 1 (or March 1) water content as one variable and the gain in water content in subsequent months as another variable. Of the four comparisons made, the

TABLE 5 – *Comparison between use of precipitation data only (X_1) and use of both snow water content (X_2) and precipitation*

Item	Feb. 1 forecast	March 1 forecast	April 1 forecast	May 1 forecast
Number of trials X_1 and X_2 is better	0	2	1	3
Number of trials about equal	3	2	1	0
Number of trials X_1 only is better	0	0	1	0

TABLE 6 – *Comparison between use of snow water content only (X_2) and use of both precipitation (X_1) and snow water content*

Item	Feb. 1 forecast	March 1 forecast	April 1 forecast	May 1 forecast
Number of trials X_1 and X_2 is better	3	2	3	5
Number of trials about equal	2	5	4	3
Number of trials X_2 only is better	0	0	0	0

TABLE 7 – *Comparison of simple correlations using precipitation data (X_1) with those using snow water content (X_2)*

Watershed	Date of forecast	Precipitation		Snow-water content		Evaluation
		$\bar{R}$	σ_R/b	$\bar{R}$	σ_R/b	
Seminoe	Feb. 1953	0.79	0.21	0.61	0.32	precip. better
Green Mtn.	Feb. 1953	0.80	0.18	0.72	0.23	precip. better
Granby	Feb. 1953	0.57	0.36	0.62	0.33	equal
Granby	Mar. 1953	0.65	...	0.62	...	equal
Big Thompson	Mar. 1953	0.55	...	0.45	...	equal
Poudre	Mar. 1953	0.32	...	0.42	...	equal
Seminoe	Apr. 1953	0.79	0.19	0.76	0.26	equal
Granby	Apr. 1953	0.73	0.21	0.80	0.18	snow better
Big Thompson	Apr. 1953	0.36	0.56	0.45	0.45	equal
Seminoe	May, 1953	0.66	0.11	0.81	0.11	snow better
Big Thompson	May, 1953	0.50	0.42	0.58	0.32	equal
Poudre	May, 1953	0.60	0.13	0.53	0.38	equal

breakdown into periods indicated either a loss or no gain in accuracy. It was concluded that the breakdown of snow water content into periods was not justified.

Use of snow-survey data only—A number of comparisons were also made between use of snow water content only and use of both precipitation and snow water content. The results are indicated in Table 6. In all of the trials indicated, precipitation data for the snowmelt period was used as a third factor in the analysis. Statistically, the use of both types of data is either equal or superior to the use of snow-survey data only. When increased sampling is considered, the desirability of using both types of data is even more apparent.

Comparison of use of only precipitation or snow-water content—Although it has been demonstrated that the use of both types of data gives better results, a comparison between the use of precipitation data only and the use of snow water content only was made, because of the probable general interest in the subject. The results are presented in Table 7. The actual statistical results are tabulated in this case, and, for purposes of comparison, the same method of evaluation used in other parts of this paper is also given.

The comparison indicates that, if used individually, there is little to choose between the two types of data. A slight advantage exists for precipitation data in early forecasts, while an almost identical advantage exists for snow water content in the later forecasts.

Combination of snow and precipitation into single factor—Since satisfactory multiple correlations could not be obtained when total winter precipitation and snow water content were used in the same analyses, because of their interdependency, the possibility of combining the two factors into a single variable was suggested.

In most cases it was arbitrarily assumed that the snow water content and the winter season precipitation would be given equal weight. This could not be accomplished by merely averaging the snow water content and the winter precipitation, since the average snow water content was generally several times the average winter precipitation. Thus, if absolute values of the two factors were averaged, a given percentage deviation from average snow water content would have a greater influence on the average snow-precipita- index than would the same percentage deviation from average winter precipitation. Therefore, the following method, which gives approximately equal weighting to the two types of observations, was generally used

$$I_x = \frac{W_a P_x + P_a W_x}{2(W_a + P_a)}$$

where

I_x = weighted average snow-precipitation index for year x
W_a = average snow water content for period of record
W_x = snow water content in year x
P_a = average winter precipitation for same period of record as for snow water content
P_x = winter precipitation in year x

In practically all watersheds the number of snow courses was either equal to or greater than the number of precipitation stations. When the snow courses greatly outnumbered the precipitation stations, an arbitrary weighting was adopted to avoid a disproportionate influence of the limited observations of precipitation.

A total of 32 comparisons were made between correlations with the weighted snow-precipitation combined factor and correlations with the in-

TABLE 8 – *Comparison between combined and individual snow-precipitation factors*

Item	Feb. 1 forecast	March 1 forecast	April 1 forecast	May 1 forecast
Number of trials combined factor better	5	7	5	1
Number of trials about equal	0	2	4	7
Number of trials individual factors better	0	0	0	1

dividual factors. The results, given in Table 8, indicate a superiority for the combined factor for February 1, March 1, and April 1 forecasts. This is given added weight when considered in connection with previous analyses, wherein it was indicated that the use of total seasonal precipitation is not as satisfactory for early forecasts as the use of October–December precipitation. Thus the combined factor not only has statistically superiority, but also allows the sampling of total seasonal precipitation. For May 1 forecasts, use of the combined factors is about equal in accuracy to use of individual factors.

Winter temperatures—Winter temperatures were investigated in an attempt to find an influence that would supplement the primary factors of snow water content and precipitation, thus narrowing the probable forecast error that exists using the primary factors only. A total of 24 trials were made using varying expressions of the winter temperature factor. Since the same relative result was evident for a given watershed for each of the four forecast dates, the results, given in Table 9, can be assumed representative of all forecast dates. The results are somewhat inconclusive. In scattered trials good statistical results are obtained using the temperature factor. In such cases the use of this factor would be desirable, because of the greater sampling of climatic influences. In most cases, however, the use of temperature factors gave unsatisfactory results.

Melt season factors—The important effect that precipitation during the snowmelt season has on the snow melt runoff was substantiated in most cases by the results of the investigations. A comparison is given in Table 10 between the $\bar{R}$'s obtained when varying parts of the melt-season precipitation were taken into account. All correlations had good σ_b/b ratios except one, as noted, hence the $\bar{R}$ comparison constitutes a good relative evaluation.

The fact that good correlations can be obtained when all factors are known, including all melt-season precipitation, is only of academic interest as far as the standard error, $\bar{S}$, is concerned, since the melt-season precipitation is unknown at the time the forecast is made. The standard error of the estimate is therefore not the one related to the high $\bar{R}$ with melt-season precipitation known, but must take into account the possible variation in the melt-season precipitation, which increases it to approximately that related to the $\bar{R}$ without melt-season precipitation.

In view of this, it might seem as well to accept the forecast equation without melt-season precipitation; however, there are distinct advantages to using this factor. Individual factors that affect runoff will be properly expressed in a forecast equation only when all factors influencing the runoff are included. The inclusion of melt-season precipitation in the equation therefore increases the reliability of the estimate of influence of the

TABLE 9 – *Value of winter temperature as a forecasting factor*

Method of expressing temperature factor	Number of watersheds in which forecasts are better	
	With temperature factor	Without temperature factor
Average September–November temperature	0	1
Average February–March temperature	0	1
Average February temperature	0	2
Average March temperature	0	2
October–December temperature excess	2	2
November–December temperature excess	0	4
January–February temperature excess	1	1
November–March temperature excess	0	1

TABLE 10 – *Comparison of use of varying parts of melt-season precipitation*

Watershed	Period of spring precipitation used	$\bar{R}$ for given cutoff date			
		Spring precipitation not used	May 31	June 30	July 31
Seminoe	April–cutoff date	0.83	...	0.935	0.946
Granby	April–cutoff date	0.80	...	0.927	0.930
Green Mountain	April–cutoff date	0.83	...	0.89	...
Seminoe	May–cutoff date	0.85	...	0.925	0.927
Granby	May–cutoff date	0.85	...	0.910	0.913
Green Mountain	May–cutoff date	0.866	0.860[a]	0.896	0.901

[a] Poor σ_b/b ratio.

factors known at the time the forecast is made, even though only the most probable or some other forecasted precipitation is used in the equation. Another advantage is the adaptability of the equation to forecast revisions as the melt season progresses, by substituting the known portion of the precipitation, as it occurs, for the assumed precipitation.

Since the standard error of a forecast, $\bar{S}$, is so important in its operational application, an equation using melt-season precipitation is not usable unless methods are available for evaluating the combined probabilities of variations in melt-season precipitation and the variations inherent in the basic equation itself, as represented by its S. Obviously the substitution in the forecast equation of spring precipitation values determined from frequency analysis is not a satisfactory method of determining the probable forecast error, as this neglects the error inherent in the equation. Conversely, the range due to probable variation in precipitation cannot be added to the probable error in the basic forecast as this would be compounding the probabilities. Since methods of combining the probabilities were not available in 1953, all forecast equations developed in that year were made without melt-season precipitation. However, with the publication of a method for making this computation [*Ford*, 1953], all correlations made in 1954 used melt-season precipitation as a factor.

From Table 10 it can be seen that but little increase in statistical accuracy of the basic equation is gained by including July precipitation. This slight increase is more than offset by the increased variability that is introduced by the inclusion of July precipitation. Accordingly, it was concluded that the melt-season precipitation factor to be used should extend only through June.

The Green Mountain correlations, and, in certain early season forecasts, those for Willow Creek and Granby, were not improved enough by use of melt-season precipitation to offset the increased variability introduced by this factor. This comparison can be tested by computing the range in the forecast, with and without the melt-season precipitation factor. However, it was not concluded that this factor was definitely non-significant; rather it was believed that in these isolated cases the investigations may have failed to determine the best expression for melt-season precipitation.

Temperatures—Limited study was made of temperatures in the early melt season, using only April temperatures. For the Green Mountain watershed this factor was found entirely non-significant, while for the Seminoe watershed its use in the May 1 forecast increased the accuracy slightly. The factor does not appear to be important enough in the basins studied to warrant undue work in its analysis.

Examples

Some of the equations adopted for use in 1954 forecasts are shown in Table 11. These represent only a small percentage of the adopted equations

Table 11 – *Examples of adopted forecast equations for 1954*

Forecast point	Forecast date	Equation	$\bar{R}$	9-in-10 chance range	
				1000 ac ft.	Pct. of April–July flow
Green Mountain	Feb. 1	$Y = 148.0 + 21.2(0.65\ X_1 + 0.35X_2)$	0.73	73	24
Green Mountain	Mar. 1	$Y = 115.0 + 19.6(0.67\ X_1 + 0.33X_2)$	0.80	63	20
Green Mountain	Apr. 1	$Y = 80.8 + 18.1(0.67\ X_1 + 0.33X_2)$	0.83	59	19
Green Mountain	May 1	$Y = -41.3 + 21.0(0.67X_1 + 0.33X_2) + 14.7X_3$	0.90	74	24
Granby	Feb. 1	$Y = -6.0 + 5.68(X_1 + 2X_2) + 19.1X_2$	0.81	60.2	28
Willow Creek	Mar. 1	$Y = 13.2 + 32.0X_2 + 2.27X_3$	0.81[a]	13.8[a]	29[a]
Willow Creek	Mar. 1	$Y = 5.8 + 5.89(0.55X_1 + 0.45X_2)$	...	...	...
Cache la Poudre	Mar. 1	$Y = -65.7 + 15.9X_2 + 9.16X_3 + 16.7X_3$	0.93	80.6	38
Big Thompson	Apr. 1	$Y = -0.9 + 4.82(0.67X_1 + 0.33X_2) + 5.47X_3$	0.88	26.0	25
St. Vrain	May 1	$Y = -15.5 + 7.29(0.49X_1 + 0.51X_2) + 3.56X_3$	0.85	34.0	41
Seminoe	Apr. 1	$Y = -558 + 110(0.78X_1 + 0.22X_2) + 68.9X_3$	0.94	194[a]	22[a]
Seminoe	Apr. 1	$Y = -369 + 30.9X_2 + 61.6X_3 - 0.22X_4 + 84.9X_5$	0.95	...	...

[a] represents average value for two equations.

Y = April–July runoff, 1000 ac ft.

X_1 = October to forecast date average precipitation in basin, inches.

X_2 = Average water content of snow courses in basin on forecast date, inches.

X_3 = April 1 (or forecast date, if later) through June precipitation, inches.

X_4 = November–December temperature excess at key point, degree-days.

X_5 = October–December precipitation, inches

and are shown as examples only. Future refinement of forecasting procedures in the light of new hydroclimatic occurrences will undoubtedly call for revision of the equations. The forecast range, where melt-season precipitation is included in the equation, includes allowance for variability of this factor.

Conclusions

The use of multiple-correlation methods for forecasting work can be aided greatly by use of high speed electronic computers which allow investigation of more factors by holding computation costs to a minimum.

The forecast procedure to be used must be determined individually for each basin and date of forecast. The choice can be guided by indices of statistical accuracy, but judgment and reasoning must also be considered.

While the results in the watersheds investigated do not establish the degree of influence of individual factors for other basins, they may be helpful elsewhere as clues in the search for increased statistical accuracy. The following general conclusions are reached relative to the influence of individual factors in the basins studied:

(a) Unless definite evidence exists concerning unreliability of an individual precipitation station, all available stations in the basin should be used in order to minimize observational error or abnormal storm distribution. The same conclusion is reached with respect to snow courses.

(b) Variations in weighting of snow courses and precipitation stations give increased accuracy only in large watersheds with wide areal variations in runoff characteristics.

(c) Exponential relationships between runoff and snow water content were not in evidence.

(d) Neither late summer precipitation nor fall and winter streamflow is a satisfactory means of expressing the effect of antecedent conditions.

(e) When winter precipitation is used as a separate factor, it is best to break the precipitation into two periods, with the dividing point being December 31. Evaluation of the relative effect of early and late winter precipitation gives different and inconclusive results in different watersheds.

(f) No increase in accuracy is gained by breaking the snow water content into time periods.

(g) The use of both snow-survey and precipitation data is clearly superior to use of only one type of data. When used individually, no clear advantage is demonstrated for either type of data.

(h) A combined snow water content - precipitation index is preferable to use of separate variables, because of the interrelationship between these factors.

(i) The use of winter temperatures as a factor appears justified in only a limited number of cases.

(j) Melt-season precipitation should be used in most forecast equations, provided proper accounting is made of the variability in this factor in determining the forecast range.

(k) Early melt-season temperatures are not uniformly significant, but may be important in individual cases.

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Observations on the Efficiency of Sub-Irrigation in Heavy Soils

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Abstract—The interest in sub-irrigation has lately been revived because of its successful application in a number of sandy soils, peats, and some heavy soils in the Netherlands. In heavy soils the difficulty is encountered that water extraction by roots tends to exceed moisture replenishment from a water table. This is related to the slow capillary movement in heavy soils and to the fact that the rate of this movement declines progressively as the soil-moisture content is further depleted by the roots. The rate can be maintained where the soil is kept moist by occasional rain storms during the period of sub-irrigation. This point is illustrated by experimental work at Rukuhia. Measurement of pasture production at various depths of water table and under varying climatic conditions showed that sub-irrigation can be quite successful if supplemented by rain; in the absence of rain sub-irrigation was quite inefficient. Some observations have been referred to which show that substantial amounts of water can be derived from a water table, even in heavy soils, where active roots penetrate close to it, but an undue rise in the level of the water table should be averted in that case.

Introduction—Early work on the possibility of satisfying water needs of plants by supply from a ground-water table yielded variable results; in some cases a beneficial and in other cases a harmful effect was demonstrated. Opinions on water-table effects on crops have thus remained divided. However, the successful application of sub-irrigation in peat and muck soils, and in some highly permeable sandy soils underlain by an impervious layer, and the stress which has been placed on the importance of sub-irrigation by Dutch workers in the last few years has led several to have another look at the possibility of sub-irrigation. A detailed review of the literature on this subject is given elsewhere [*van't Woudt* and *Hagan*, in preparation].

A considerable amount of data are now available on the handling and the effect of sub-irrigation in peat and muck soils, but little is known about the possible effect under field conditions of a water table kept close to the surface in heavy soils. Although data have been published in the Dutch literature on favorable effects of a high water table on crops grown in heavy soils, virtually all data seem to have been collected under conditions where sub-irrigation was aided by rainfall; no data have come to hand which could show how effective sub-irrigation is under field conditions in heavy soils in the absence of rain. This paper reports some work which draws attention to the difficulties which are encountered under such circumstances.

Experimental procedure—Use was made of an existing tile drain system extending over two acres of low-lying land in Te Kowhai clay loam, surrounded by about 50-ft long slopes. Two main three-inch tile drains each drain about one acre of land. A few side-drains discharge in one of the main drains, the set-up resembling somewhat a herring-bone pattern (Fig. 1). Both main drains discharge into a ditch.

The drainage from one of the main tile drains was uninterfered with and the water table in the part of the field covered by this drain fell to about three feet below the surface during the summer months. This part of the field was used for investigating the effect of a low water table on pasture production.

Close to the outlet of the other main drain a square concrete structure (reservoir), measuring three by three feet and having a depth of 30 inches, was built into the soil. The line of tiles ran through this reservoir. The two tiles crossing the concrete wall on opposite sides were cemented in, while the tile in the center of the reservoir was taken out. The tile nearest to the ditch was provided with a block plug of such a construction that the outlet of the reservoir could be opened or closed at will. The block plug consisted of a metal plate with a rubber ring facing the tile opening which, by means of a strong spring and under water pressure, caused the tile to become virtually impervious. The metal plate could be withdrawn from the tile opening, being hinged, by sliding a metal bent rod and pulling the rod. The tile was kept open when required by hooking the bent top of the rod around a fixed fence wire above the ground surface.

Water was applied to the highest end of this drain from a pipeline when required. The quantity of water applied has not been measured. The duration of the application was determined by the height of the water table on the experimental area.

As the area had a fall of several feet over a dis-

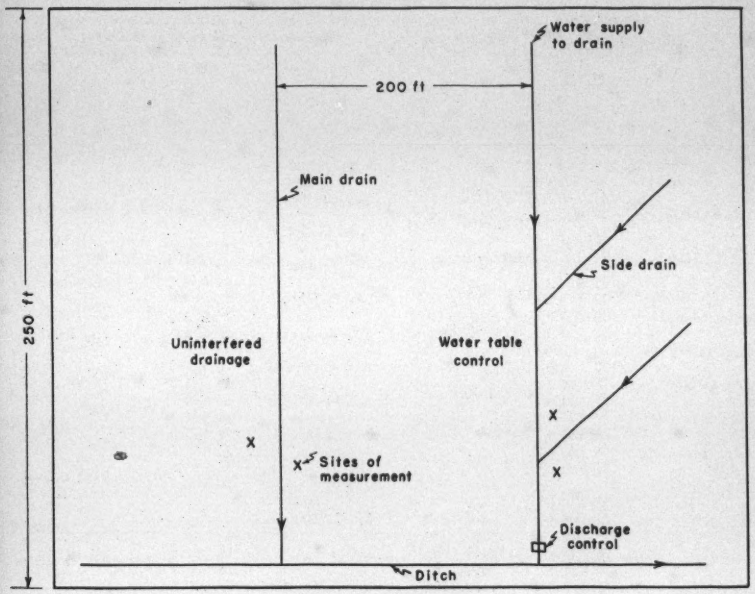

FIG. 1 – Experimental set-up

tance of 200 ft from the highest end to the outlet of the drain, it was not possible to maintain the water all along the main drain at the same level. This situation was made use of at a later stage to measure pasture production at various levels of ground water.

The level of the water table throughout the experimental area was measured by means of 42, regularly-spaced, observation wells of four inches diameter and three feet depth.

Chemical analysis of the soil of the two parts of the area compared, that with controlled and that with uncontrolled water table, yielded no differences of significance. Fertility in the two parts appeared the same.

Pasture production was measured by mowing the sward by a sickle-bar mower within movable frames covered by wide-meshed wire netting. The area covered by these frames was $\frac{1}{1000}$ or $\frac{1}{1500}$ acre. After each measurement the frames were placed in a new position. The area was grazed by sheep.

Results—The production figures, the percentage dry matter in the herbage and the water table level at the site of measurement are shown in Tables 1 and 2 for the period January 1953 until August 1954. Climatological data of interest measured during this period are shown in Table 3. The three periods of moisture deficiency as defined by Table 3 are discussed below.

(1) A small moisture deficiency arose at the end of January 1953 and this deficiency increased during February and March. At the end of March moisture in the surface soil was largely repleted by rain. During the early part of this period (Jan. 23 until March 13) pasture yield was maintained at a satisfactory level where the water table was at 18 to 24 inches, while it dropped to a low level where the water table fell below 30 inches. The total yield during this period was 2830 lb and 620 lb for respectively the high and the low water table. From March 13 until April 2 no growth was measured at the low water table, whereas at the high water table the yield was maintained at a level just over half that measured on sprinkler-irrigated pastures. Thus, as the moisture deficiency increased a high water table appeared to become less effective in supplying adequate moisture for growth. A favorable effect of a high water table

TABLE 1 – *Pasture production at different levels of water table, area with controlled water table*

Period of growth	Dry matter: Per cent	Dry matter: Per acre per day	Dry matter: Average	Dry matter: Total per acre	Depth to water table
1953		lb	lb	lb	inch
Jan. 23–Mar. 13	15.5	55.0	57.8	2830	18–24
	17.2	60.6			
Mar. 13–Apr. 2	15.0	32.2	21.3	430	18–24
	15.4	9.3			
Apr. 2–May 7	14.6	20.4	25.9	910	24
	14.2	31.4			
May 7–July 2	11.4	19.1	19.0	1060	
	12.4	18.8			
July 2–Aug. 11	19.2	3.3	6.3	250	About 24
	18.5	9.3			
Aug. 11–Sep. 14	20.5	0.6	1.8	100	
	20.1	2.9			
Sep. 14–Nov. 2	18.0	46.3	40.2	1970	
	21.8	34.0			
Nov. 2–Dec. 21	22.2	33.3	36.1	1770	16
	25.4	38.9			
Dec. 21–Jan. 21, 1954	26.2	50.8	54.9	1700	14–18
	24.9	59.0			
1954					
Jan. 21–Mar. 1	35.2	9.6		370	26
	23.7	8.1		320	23
	25.1	19.2		750	15
	20.1	35.8		1400	9
	19.8	51.5		2010	6
Mar. 1–Apr. 7	13.3	38.3		1420	30
	13.1	26.0		960	26
	15.0	27.4		1010	21
	14.7	12.5		460	14
	13.5	17.5		650	8
Apr. 7–May 21	20.4	25.0		1100	20
	18.2	25.4		1120	13
	20.2	21.3		940	11
	21.2	20.2		890	5
	20.3	20.4		900	5
May 21–Aug. 4	24.0	1.4		105	27
	17.8	15.7		1180	27
	20.2	6.9		520	16
	20.3	9.3		700	14
	20.3	8.9		670	8

TABLE 2 – *Pasture production at different levels of water table, area with uninterfered drainage*

Period of growth	Dry Matter: Per cent	Dry Matter: Per acre per day	Dry Matter: Average	Dry Matter: Total per acre	Depth to water table
		lb	lb	lb	inch
1953					
Jan. 23–Mar. 13	22.2	11.3	12.7	620	30–34
	21.6	14.1			
Mar. 13–Apr. 2	...	...	0.01	...	30–34
	18.9	0.02			
Apr. 2–May 7	13.4	17.2	14.5	510	
	14.6	11.7			
May 7–July 2	12.5	8.9	16.9	950	
	12.9	24.8			
July 2–Aug. 11	18.6	5.5	3.0	120	Below 24
	23.1	0.5			
Aug. 11–Sep. 14	20.5	1.5	2.9	100	
	19.2	4.2			
Sep. 14–Nov. 2	16.8	50.3	40.8	2000	
	14.6	31.3			
Nov. 2–Dec. 21	29.4	45.0	48.4	2370	32
	27.0	51.7			
Dec. 21–Jan. 21, 1954	35.8	15.5	12.1	380	Below 32
	36.3	8.7			
1954					
Jan. 21–Mar. 1	...	...	...	...	Below 32
	...	...			
Mar. 1–Apr. 7	18.5	32.8	35.0	1300	Below 32
	16.4	37.2			
Apr. 7–May 21	19.4	20.5	22.1	970	31
	19.8	23.6			
May 21–Aug. 4	20.0	11.6	9.8	740	26–27
	20.0	8.0			

seemed to persist in April; during this month the yield from sprinkler-irrigated pastures remained also substantially higher than that from non-irrigated pastures.

(2) A small moisture deficit arose during September 1953 which seemed to have little impact on pasture production; little response from sprinkler irrigation was obtained during that month.

(3) A moisture deficit started to develop at the end of November 1953 and it increased till the end of February 1954. In the beginning of March the soil was repleted with moisture, following about six inches of rain.

During the next period, December 21 until January 21, 1700 lb per acre was measured at a water table of 14 to 18 inches, but only 380 lb at a water table below 32 inches; at that time it had become apparent that pasture yield varied considerably according to the depth of the water table, so that a number of new frames were placed.

During the next period of growth, from January 21 until March 1, that is the time when the moisture deficit in the soil built up to its highest level, pasture production was the greater the closer the water table to the surface. The total yield per acre is shown in Table 4.

Thus, during the time of high moisture deficit, a water table at 15 or 23 inches was quite inadequate to sustain pasture production, an observation already made during the preceding summer. At that time more moisture seemed to be provided where the water table was closer to the surface, in fact so close as to become impracticable under farming conditions.

A conclusion that capillary rise from a water

TABLE 3 – *Excess rainfall over open water surface evaporation in inches*[a]

Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
1953	−0.40	−2.17	−0.70	3.45	5.66	6.23	7.01	2.63	−.64	0.80	−0.92	−1.90
1954	−5.47	−3.53	3.91	2.27	3.67	3.36	4.01	3.38	...	...	...	...

[a] Open water surface evaporation was measured from a standard, round, concrete New Zealand Meterorological Service tank, three feet deep and three feet in diameter, estimated to measure 15 pct in excess of lake evaporation.

TABLE 4 – *Relationship of yield to depth to water table*[a]

Depth water table	Yield per acre
inch	lb
26	370
23	320
15	750
9	1400
6	2010

[a] During March, when moisture was plentiful, the relationship was almost reversed.

TABLE 5 – *Percentage of available moisture in the soil above the water table after a period of high evaporation and low rainfall*

Depth below surface	Depth to water table, 24 inches		Depth of water table, 30 inches	
	Date of measurement		Date of measurement	
	Jan. 6, 1954	Jan. 14, 1954	Jan. 6, 1954	Jan. 14, 1954
inch				
3	12	12	0	5
	12	10	5	5
6	15	10	10	12
	10	15	0	25
9	17	15	20	17
			15	30
12	15	17	27	27
			35	35
15	35	30	25	17
	40	15	20	18

table at about 15 inches depth did not supply adequate moisture for growth at times of high moisture deficiency over an extended period is supported by the following measurements: (1) The percentage of available moisture in the soil above the water table had fallen to a very low level after a dry spell of several weeks as shown by data in Table 5. Only where the water table was at five and nine inches depth did the soil remain moist throughout. Similar data illustrating the inefficiency of capillary rise under such conditions were recently given by *Bouyoucos* [1953]. (2) The level of the dry-matter percentage of the herbage is in line with these observations. Well-sprinkler irrigated pastures always show a dry matter percentage of about 15 pct during the summer months, while that on non-irrigated pastures is generally 20 pct or more during that time. During the first relatively rainy months of 1953 this percentage remained at a low level where the water table was kept high, indicating adequate moisture supply, but during the dry summer of 1953–54 this percentage reached a level of that of non-irrigated pastures.

The findings are in agreement with observations on the relationship between capillary conductivity and moisture content as studied by *Moore* [1939] in his experiments on capillary rise from a water table. If the rate of moisture depletion by roots is greater than the rate of replenishment, the rate of capillary rise slows down progressively as the soil dries out further. The situation is somewhat more favorable where active roots penetrate to just above or even below the ground water surface [*West*, 1933; *Fox* and *Lipps*, 1955]; this, however, does not apply to the pastures studied where effective root concentration is virtually confined to the top six inches of soil.

The successfulness of sub-irrigation in heavy soils in Holland seems thus related to recurrent summer rains which keeps the surface soil at a sufficiently high moisture level for capillary rise to be a factor of significance in crop production. Recent data by *Wind* [1955] on this problem in Holland allow an interpretation which supports this conclusion.

The success of sub-irrigation in sandy soils and in peat can be explained from the high rate of capillary rise from a water table, which allows the rate of moisture depletion by roots to be matched by the rate of replenishment. In heavy soils this rate of replenishment tends to fall behind the rate of removal. However, it seems that even in that case sub-irrigation can still be successful if it is supplemented by natural rain so that a relatively high rate of capillary rise is maintained in moist soil. It could also be successful where certain plants are able to send active roots into the fringe just above, or even below the water table. However, in that case considerable damage to the crop can be done if the water table is raised, even if only for a short period, by killing the roots.

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Infiltration Frequency on Ralston Creek Watershed

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Abstract—The frequency of occurrence of infiltration rates as indicated by an infiltration index was computed from the records of the Ralston Creek watershed near Iowa City, Iowa.

Introduction—The objective of this paper is to relate the frequency of occurrence of infiltration rates as indicated by an infiltration index for the Ralston Creek watershed on which early records were first published by *Mavis* and *Soucek* [1936]. Indices were derived for 92 selected storms from 29 years of record [*State University of Iowa*, 1924–1953].

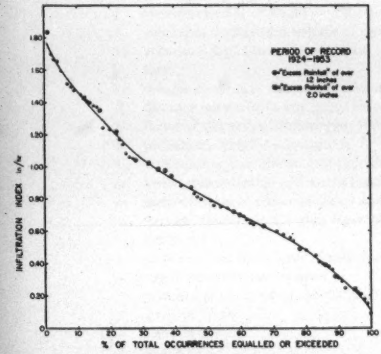

FIG. 1 – Infiltration-index frequency curve for all analyzed storms

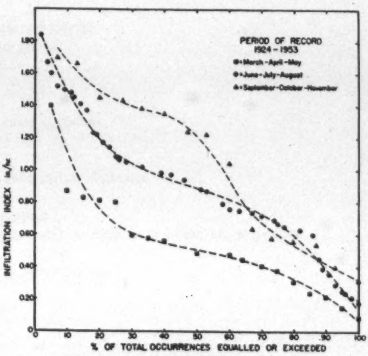

FIG. 2 – Infiltration-index frequency curves showing seasonal effect

Ralston Creek is approximately three square miles in area of which about 42 pct is cropped, 38 pct is permanently pastured, and about 20 pct is in timber, roads, yards, and orchards. The cropping percentage has not varied more than ten per cent from the figure given for the period of record with the exception of 1934 when a severe drouth occurred. The land surface is rolling, the average slope being about nine per cent. The predominant soil type is a weathered loess of a silt loam to a silty clay loam texture.

Procedure—The infiltration index used is similar to the ϕ index defined by *Linsley*, *Kohler*, and *Paulhus* [1949, pp. 426–427]. The estimated depth of 'excess' rain minus the depth of runoff was divided by the duration of excess rain plus an arbitrary five minutes for overland flow to produce the index. The excess rain is defined as that rainfall which fell at a rate greater than the rate of infiltration. All storms which produced peak discharges of less than 0.03 inch per hour and which had periods of excess rain of less than 20 minutes were omitted. Storms with uneven rainfall distribution and storms in which it was difficult to associate a runoff hydrograph with the excess rain were also omitted. Storms for March through November were studied.

Results—Figure 1 summarizes the results. Points were plotted for each index, the circled points representing storms of excess rainfall of 1.2 inches or more. The history of infiltration rates on the Ralston Creek watershed as indicated by the described index shows that a wide range of infiltration rates may be expected even where vegetation is held relatively constant. Indices for storms producing greater amounts of excess rainfall revealed no discernible tendency to have lower values as evidenced by the scatter of points along the curve. Figure 2 shows the effect of season, although there were too few storms in the spring and fall to describe a well-defined curve. The distribution of indices for March, April, and May revealed much lower infiltration rates than the rates indicated by

the summer and fall distributions. Most of the indices for the fall period fell above those for the summer period, although there were too few fall storms to define the relationship accurately. It should be kept in mind that where surface storage is relatively small the index is a conservative estimate of the actual infiltration rate on a watershed of mixed cover, since it is impossible to define clearly the rainfall intensity required to insure runoff from the whole watershed for a given cover, season, and antecedent moisture condition.

Duplicated copies of the original data from which the indices were determined may be obtained upon request to the authors.

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Dispersion of a Moving Salt-Water Boundary Advancing Through Saturated Sand

PAUL R. DAY

Abstract—When salt water displaces fresh water in sand the boundary between the two liquid phases becomes diffuse after a short period of flow. The dispersion of salt may occur at a much greater rate than can be expected by ion diffusion. The effect has been attributed to a mechanism referred to here as hydrodynamic dispersion, a general phenomenon arising from the fact that the velocity of the moving stream varies from point to point in the porous system.

The mathematical treatment of the problem is based upon a statistical theory developed by Scheidegger. Equations have been derived here for the dispersion of salt water injected in the stream. The theory has been tested by displacing pure water with salt water in a column of saturated sand and determining the concentration of effluent as a function of time. The measured concentrations vary with time in approximately the manner predicted by theory.

Notation—The following symbols are used.

v	average velocity of liquid = macroscopic velocity/E
E	volume of liquid/total volume of porous system
V_0	volume of liquid in a drop ('cluster')/E
t	time
δV	volume element of the porous system
R	distance outwards to any point from center of cluster
D	factor of dispersion [*Scheidegger*, 1954]
ϕ	probability density (dimensions, L^{-3})
σ_D	root-mean-square distance of particles from center of cluster
c_0	initial concentration of tracer substance
c	concentration of tracer at time t and depth x
x_0	vertical thickness of a thin layer of salt water = volume of liquid/($E \times$ area of surface)
t_0	time required for a layer of salt water to enter the sand
x	depth below surface of sand
$\hat{x}$	position of the crest of the distribution
z	$(x - vt)/2\sqrt{Dt}$
z'	$(x - vt')/2\sqrt{Dt'}$
t'	$t + t_0$

Introduction—The nature of the problem has been well expressed in a recent publication dealing with sea water intrusion [*Sanitary Engineering Research Laboratory*, 1955]: "A type of mixing distinct from diffusion occurs at the interface between sea water and fresh water whenever the interface shifts. This is due to the fact that a part of one phase is not displaced as readily as the rest. On a microscopic scale, a film of the displaced phase may be left behind on the sand grains while most of the liquid is swept forward."

The phenomenon has been described in greater detail by *Kaufman* and others [1955], who have shown from lysimeter studies of soil that a large amount of dispersion of chloride ion occurs at the interface between the intruding phase (containing chloride) and the displaced, initially chloride-free, phase. They have explained the effect on the basis of the variations of the local velocity vectors (in strictly laminar flow) from the average velocity vector. Similar observations have been made by *Yuhara* [1954], who has given a mathematical interpretation of the effect.

The dispersion of liquids moving through porous media is evidently a general phenomenon. For example, *Kitagawa* [1934] demonstrated that lateral dispersion of chloride (originating at a point source) occurred during horizontal flow of water through sand, giving a normal distribution of chloride laterally with respect to the flow axis. The conventional application of hydrodynamics to flow through porous media does not explain these facts because average velocities are considered without reference to velocity distributions.

Scheidegger [1954] has developed a general theory, based upon statistics, that predicts the manner in which the particles of fluid moving through a porous medium are distributed by the

motion, taking into account the fact that the velocities are distributed in a definite, but generally unknown manner. His treatment is relevant to the problem of the dispersion which occurs during the displacement of fresh water by salt water, but will require some explanation.

Dispersion of liquid during flow through sand—A simple flow situation is assumed: A shallow layer of water is maintained (by continuous additions) on the upper surface of a horizontal bed of saturated sand, and water is allowed to move vertically downwards through the sand with steady, laminar motion.

Consider the movement of a single drop of liquid, composed of a large number of small, equal, volume elements referred to herein as 'particles.' Let the drop be approximately isometric (for example, spherical or cubical). The drop will be carried into the interstices of the medium by the surrounding liquid, and the particles will soon be interspersed with particles from other drops. The particles originating from a given drop will be referred to as a 'cluster' of particles to emphasize their common origin.

A clear distinction will be drawn here between the true streamlines and the conventional streamlines commonly used to describe flow in porous media. The latter can be described as lines drawn everywhere tangent to the average velocity vectors (vertical, in the present case). The true streamlines are defined as lines drawn everywhere tangent to the actual velocity vectors. They are obviously different from the conventional streamlines, and vastly more complicated geometrically.

Each particle will travel in a path determined precisely by the hydrodynamic conditions which it encounters at every moment and, in the steady state, each particle will be followed by other particles in the same path. Every region of the fluid must conform to the mechanical requirement that the sum of the forces, including viscous shear forces, must be zero [*Sommerfeld*, 1950, p. 77]. Furthermore, the (true) streamlines must never intersect, although they may be sinuous and intertwined.

One can see geometrically that the particles of a given cluster can spread through a broad region in a general downstream direction, while particles of other clusters can intrude, or intermingle, and fill the intervening space. The spreading and interspersion of particles can take place without crossing of paths because of the three-dimensional geometry of the system.

Another feature of the flow which should be noted is the variation of velocity along the streamlines. A particle may be delayed or accelerated at various points along the path. Its average velocity over the entire length of path may differ greatly from the average velocity of the whole fluid, a fact that can be appreciated readily from a consideration of the distribution of velocities in a simple capillary tube.

The preceding remarks indicate a limitation of the conventional description of flow in porous media. Although the conventional streamlines describe correctly the composite direction of flow they give a misleading result when one wishes to identify the fluid in a given downstream region with its upstream source. A given particle may be found far from its expected position at a given time t after entry, if by 'expected position' is meant its location on the conventional streamline on which it originated at a distance vt along its path. In spite of this limitation, the conventional streamlines may be used for describing the movements of clusters of particles.

A cluster of many particles originating in a small region will follow a composite path which will be simpler than the paths of the individual particles. The center of the cluster (defined as the terminus of the average position vector of the particles) will travel along the conventional streamline with a velocity v, the average velocity of the entire fluid. However, the complicated flow geometry described above for individual particles will permit the intrusion of particles from neighboring clusters with the result that each cluster will spread (or disperse) while it progresses through the medium. The effect will be referred to as 'hydrodynamic dispersion' to distinguish it from the ordinary diffusion phenomenon.

Scheidegger's [1954] analysis furnishes the following conclusions regarding the dispersion of the fluid: The probability that a given particle, after a time t, will be found in the volume element δV, located a distance R in any direction from the expected position of the center of the cluster at that time will be equal to

$$\varphi \delta V = (4\pi Dt)^{-\frac{3}{2}} \exp(-R^2/4Dt)\delta V \qquad (1)$$

where φ denotes the probability density.

One may note from (1) that the particles of the cluster become normally distributed, with $\sigma_D = \sqrt{2Dt}$, along any diameter passing through the center of the cluster, and with the maximum (or crest) at the center. The quantity $2D$ represents the time rate of increase of the mean square distance of the particles in any given direction from

the center of the cluster. Scheidegger has called D the 'factor of dispersion.' The spherical symmetry expressed by (1) will be fully developed after the cluster has spread sufficiently to overcome the bias caused by its original arbitrary shape.

The probability equation leads directly to an equation for the dispersion of a tracer substance (for example, salt) dissolved in the original drop, assuming that the remainder of the liquid is initially free of tracer. Let V' represent the volume of liquid in the drop, and let E equal the soil porosity (the proportion of total soil volume occupied by liquid). The volume V_0 of soil required to contain the drop will be equal to V'/E, and the amount of solute contained in the volume V_0 immediately after entry will be equal to c_0V_0E, where c_0 is the initial concentration of solute in the liquid phase. Now, consider the amount of solute contained in the volume element δV at a given point in the soil at a later time t. This amount will be equal to $cE\delta V$, where c is the concentration of solute in δV. Therefore, the proportion of solute in δV, relative to the original amount in V_0, is equal to $cE\delta V/c_0EV_0 = c\delta V/c_0V_0$. This proportion corresponds physically to the mathematical probability $\varphi\delta V$ expressed in (1). Therefore, by substitution in (1)

$$c = c_0V_0(4\pi Dt)^{-\frac{3}{2}} \exp(-R^2/4Dt) \qquad (2)$$

The probability relation (1) leads to the prediction that a tracer substance will disperse, along with the liquid in which it is dissolved, in the characteristic manner described by (2). The center of the cluster (the 'expanding' drop of fluid) will move along a conventional streamline with a velocity equal to the average velocity of the entire fluid. The concentration of salt at the center will decrease with time according to the equation $c_{max} = c_0V_0(4\pi Dt)^{-\frac{3}{2}}$. The salt will be distributed symmetrically in all directions from the center in accordance with the normal Gaussian distribution, with $\sigma_D = \sqrt{2Dt}$.

Dispersion of a thin layer of salt water—The preceding analysis gives a basis for predicting the amount of dispersion of a thin layer of salt solution entering the surface at $t = 0$, preceded and followed by pure water. Let 0 be the origin of coordinates at the surface of the sand, with the x-axis directed downwards (Fig. 1). Let P represent a point on the vertical axis at a depth x below the surface and let δV be a volume element at P. A drop of

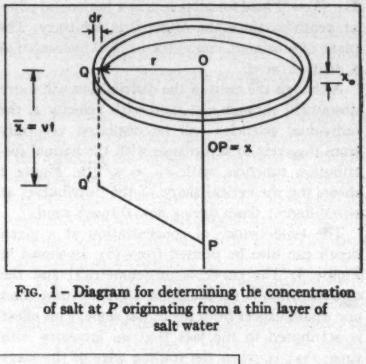

FIG. 1 – Diagram for determining the concentration of salt at P originating from a thin layer of salt water

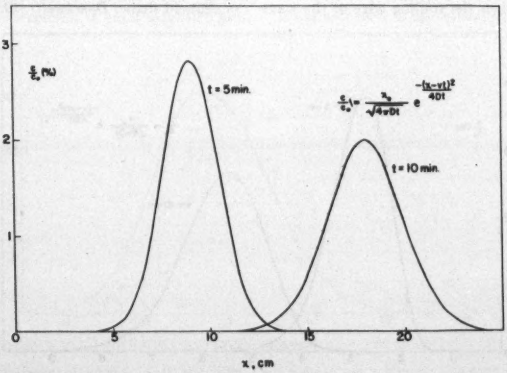

FIG. 2 – Theoretical distribution of salt with depth at two different times; $x_0 = 0.1$ cm, $v = 1.811$ cm/min, $D = 0.20$ cm²/min

salt water entering at Q will reach a point Q' at depth $\bar{x} = vt$ at time t and will contribute to the volume element δV (at P) an amount of salt equal to

$$c_0 V_0 (4\pi Dt)^{-\frac{3}{2}} \exp\{[-r^2 - (x - vt)^2]/4Dt\}\delta V_0 \quad (3)$$

The total salt contribution per unit volume at P from all volume elements in a thin layer of thickness x_0 will be

$$c = \int_{r=0}^{r=\infty} c_0 (4\pi Dt)^{-\frac{3}{2}} \exp\{[-r^2 - (x - vt)^2]/4Dt\} x_0 \times 2\pi r dr \quad (4)$$

where V_0 of (2) has been replaced by $x_0 \times 2\pi r dr$. One obtains by integration

$$c = c_0 x_0 (4\pi Dt)^{-\frac{1}{2}} \exp[-(x - vt)^2/4Dt] \quad (5)$$

Eq. (5) will hold for all points in a horizontal plane at depth x, since the origin 0 is arbitrary. The plane of maximum concentration will be located at a depth $\bar{x} = vt$.

Although the crest of the distribution will move downward through the sand with velocity v, the individual particles will be displaced vertically from the crest in accordance with the normal distribution function, with $\sigma_D = \sqrt{2Dt}$. Figure 2 shows the theoretical shape of the distribution at two different times during flow through sand.

The time-history of concentration at a given depth can also be plotted from (5), as shown in Figure 3. The curve is unsymmetrical and the concentration is sustained for a greater time than one would expect from the initial slope. This effect is attributed to the fact that σ_D increases with time; that is, when the trailing edge of the wave has reached the given level the particles will have been dispersed to a greater extent than when the leading edge had been at the same level.

Eq. (5) shows that the lateral components of dispersion cancel out, or neutralize one another when the average flow vectors are unidirectional throughout the fluid. Therefore one may conclude that vertical impermeable boundaries will not affect the vertical distribution of salt during vertical flow.

One may verify by differentiation that (5) is a solution of the differential equation

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial X^2} \quad (6)$$

where $X = (x - vt)$. Eq. (6) is identical in form with the differential equation of diffusion, but arises physically from an entirely different cause.

Dispersion of salt in the total displacement of fresh water by salt water; thick layers—The solution of (6) for the displacement of fresh water by salt water is

$$c = c_0 \int_{z=-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2} dz \quad (7)$$

where $z = (x - vt)/\sqrt{2Dt}$. Eq. (7) represents the sum of the salt contributions at a depth x made at time t by successive thin layers of salt water located upstream with respect to the moving interface. The solution is analogous to that of the diffusion equation [*Barrer*, 1941, p. 9]. Eq. (7) can be evaluated by means of standard tables of the normal probability integral.

The distribution of salt in the moving salt-water front is represented in (7) as a symmetrical curve of sigmoid shape. *Danckwerts* [1953] has reached a

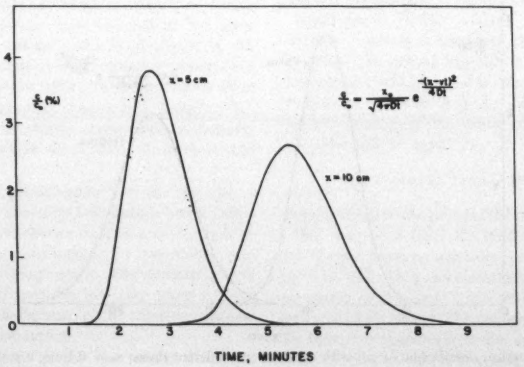

FIG. 3 – Concentration as a function of time at two different depths (same conditions as Fig. 2)

similar result by a different approach to the problem. The 'thickness' of the diffuse boundary (represented arbitrarily by the distance between the points, c/c_0 = 15.9 pct and c/c_0 = 84.7 pct) is equal to $\sqrt{2Dt}$.

When pure water displaces salt water, the distribution of salt can be determined from (7) by assigning $z = \infty$ and $z = z$ as the upper and lower limits of integration. This is equivalent to subtracting the direct solution of (7) from c_0.

The preceding results can be applied to the case of a thick layer of salt water, whose leading edge enters the surface of the water-saturated, salt-free, sand at $t = 0$, and whose trailing edge is followed by pure water at $t = t_0$

$$c = c_0 \int_{z=-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2}\, dz + c_0 \int_{z'}^{z'=\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2}\, dz = c_0 \int_{z}^{z'} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z^2}\, dz \quad (8)$$

where $z = (x - vt)/\sqrt{2Dt}$, $z' = (x - vt')/\sqrt{2Dt'}$ and $t' = t + t_0$. Eq. (8) represents the sum of the solutions for leading and trailing edges, and expresses the concentration as a function of time and depth. The reverse case of a thick layer of pure water displacing and followed by salt water may be solved by deducting from c_0 the result of (8).

Eq. (8) reduces to (5) when t_0 is infinitesimal for then $dz = (z' - z) = v(t - t_0)/\sqrt{2Dt} = x_0/\sqrt{2Dt}$.

Experimental tests—Two experiments were carried out to test the application of the foregoing equations to the dispersion of salt water supplied at the surface of a column of water-saturated sand.

TABLE 1 – *Sieve analysis of Ben Lomond sand*

Sieve size	Per cent by weight	Sieve size	Per cent by weight
mm		mm	
1–2	0.2	0.10–0.25	75.9
0.5–1	5.7	0.05–0.10	2.5
0.25–0.5	14.8	0–0.05	0.9

The sand was a fine-grained clean quartz sand having well-rounded grains (see Table 1 for sieve analysis). It was placed in a galvanized iron cylindrical container, of diameter = 10.5 cm, with a multiperforated bottom, and was filled to a depth of 26.0 cm (volume of pack = 2250 cm³). The volume of water held by the sand when saturated to the fullest extent possible by flooding was equal to 845 cm³.

Water was supplied from a constant level device and maintained at a depth of one cm on the surface of the sand. An alternate supply bottle containing 0.14 N NaCl was used when required. The effluent was collected in increments at suitable times and analyzed chemically for chloride ion.

Experiment 1—Water was passed through the column for two days and at a given moment the water on the surface was replaced by 85 ml of salt solution, giving a depth of one cm of salt water on the surface. The salt water was allowed to subside and fresh water was supplied immediately after the salt solution had entered the sand. The results are shown in Figure 4.

The theoretical curve was computed from (8), using t_0 = 1.44 minutes (time required for the salt water to enter), v = 1.811 cm/minute, and x = 26.0 cm. Because D was not known initially, it was necessary to use several trial values, selecting

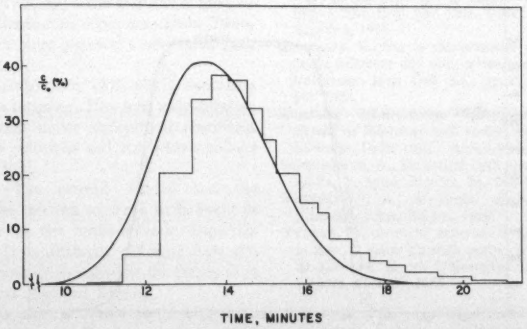

FIG. 4 – Concentration of chloride in effluent (Exp. 1); volume of salt solution/volumetric capacity of column equals ten per cent

as the best value the one (D = 0.20 cm²/min) which gave approximately the correct spread, and a maximum value of c/c_0 approximately equal to the maximum observed experimentally. The calculated curve had the proper shape, judging from the shape of the experimentally determined distribution polygon, but the crest of the distribution lagged behind the predicted crest by approximately one-half minute. The discrepancy was probably due to the momentary change of head during the addition of the salt water, slight changes in velocity during the experiment, and probably other reasons having to do with experimental control of conditions.

The procedure for fitting the theoretical curve to the experimental data was arbitrary only with respect to the selecting of D. Since the latter was the only adjustable parameter, the curve-fitting procedure constituted a determination of D for the given system.

Experiment 2—The second experiment was similar to the first, except that a greater volume of salt water (one liter) was supplied at the surface to replace the fresh water. The experimental arrangement was the same as before and the same column of sand was used (pressure head at surface = one cm). However, water had been flowing through the sand for seven days following the previous experiment, and the average velocity (v) had decreased from 1.811 cm/minute to 0.626 cm/minute because of the decreased permeability

The results are shown in Figure 5 and compared with the theoretical curve calculated from (8) using a value of D = 0.080 cm²/minute. (t_0 = 50 minutes = time required for the salt water to enter the surface.) The concentration at the leading edge of the advancing front (left branch of polygon) increased at a slightly more rapid rate than shown in the calculated curve, but better agreement was obtained for the trailing edge.

The plateau on the rising branch of the polygon was caused by taking too large a sample at this point, and does not indicate a real discrepancy between experiment and theory. A similar difficulty occurred with the last increment on the falling branch, and for this reason the polygon was terminated arbitrarily on the graph to avoid a misleading interpretation. The total amount of salt recovered was equal to 99.3 pct of that added, the difference being attributed to experimental error.

The decrease in D from 0.20 to 0.080 cm²/minute from the time of the first to that of the second experiment indicates that some of the factors which cause a change in permeability may also cause a change in D, as suggested in Scheidegger's discussion of the dispersion factor. (Note, in this connection, that the hydraulic gradient, 1.038, was equal in the two experiments.)

Discussion; relation between dispersion and diffusion—The analogy between the dispersion phenomenon and true diffusion is close because the basic differential equation and its mathematical solutions are identical for the two phenomena. Dispersion may often be more important than diffusion in bringing about a redistribution of dissolved solutes when water moves through soil, and this is certainly true in the present experiment. The statement can be supported by the following argument.

Assume that the results obtained in Experiment 2 were due entirely to diffusion, and that dispersion by the mechanism postulated in the preceding

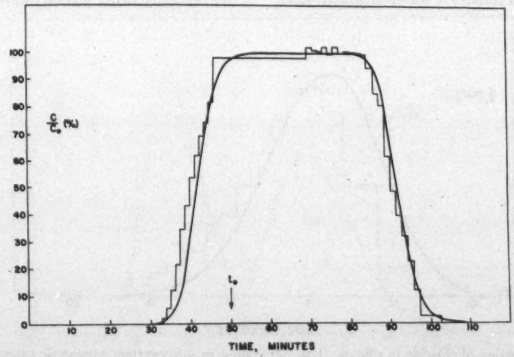

FIG. 5 – Concentration of chloride in effluent (Exp. 2); volume of salt solution/volumetric capacity of column equals 118 pct

pages was negligible. The amount of diffusion would be given by (8), where D in this case is the coefficient of diffusion. (This would be an overestimate, since the sand will partly obstruct the free diffusion of ions.) The diffusion wave would progress through the column with velocity v, as given in the experiment, and the salt would be distributed about the central plane as in (8). However, the coefficient of diffusion for sodium chloride in water is only 0.00078 cm²/min, as compared with $D = 0.080$ cm²/min determined in Experiment 2. Hence, the wave would have had to travel approximately one hundred times as long a time in order to have brought about by diffusion the amount of spreading demonstrated in the present case, or, in terms of distance, the distance of travel through the sand would have had to be one hundred times as great.

The part played by diffusion in the 'longitudinal mixing' phenomenon [*Danckwerts*, 1953; *Kaufman* and others, 1955] should not be ignored even when D greatly exceeds the coefficient of diffusion. Obviously, diffusion must occur whenever a sharp concentration gradient occurs in the liquid phase. Although the hydrodynamic dispersion mechanism brings close together the particles originating in different parts of the flow system, and intersperses them, it does not completely mix them because the streamlines never intersect. The final stage of mixing must depend upon ionic and molecular diffusion, which will become most effective when two streamlines carrying liquid of different chemical composition come close together.

The factor of dispersion D will be small when squares of the velocities are grouped closely around the mean square velocity. This situation will occur when the hydraulic gradient is small or when the size distribution of pores is narrow. Diffusion will play a more prominent role under such conditions.

Eddy diffusion [*Dryden*, 1939] will be important when the flow is turbulent. However, eddy diffusion can be neglected under agricultural conditions where the flow velocities and Reynolds numbers are generally low.

Conclusions—The present results, and the results of others referred to, leave little doubt as to the reality of the hydrodynamic dispersion phenomenon. It is distinctly different from diffusion and can easily overshadow the latter, as in the experiments reported herein.

Scheidegger's theory describes the dispersion mechanism mathematically for a viscous fluid moving through a porous solid whose openings are random in shape, size, and orientation. Although actual porous media may differ greatly from the 'completely disordered' pattern assumed in the derivation, one can determine by experiment the extent to which such deviations will affect predictions based upon the ideal model.

The experiments are too limited to constitute verification of the theory, but the variations of effluent concentration with time are sufficiently similar to the theoretical variations to indicate that the theory is useful as a working hypothesis.

An important effect of the hydrodynamic dispersion mechanism is to bring about extensive dilution of dissolved solutes added in limited amounts to the surface of the soil (Fig. 2) and displaced downwards by moving water. A second important and related effect is the spreading of the solutes far beyond the limits of the streamlines defined in conventional soil-moisture theory [*Kitagawa*, 1934]. These two effects have an obvious bearing on such matters as the distribution of plant nutrients in soil and the effectiveness of leaching.

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Permeability and Infiltration Relationships in One Dimensional Infiltration in a Uniform Soil

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Abstract—Equations are developed for the relationship between infiltration rate and time for one dimensional flow in a uniform soil of constant permeability. The depth of ponded water, the permeability of the soil and the moisture deficit in the transmission zone are the principal parameters. The equations are compared with experimental data with reasonably satisfactory results in view of the restrictive hypotheses.

Introduction—The infiltration rate of a soil and its permeability are two important experimentally determined parameters of any infiltration system. Both have been observed to vary with time, the former more frequently and to a greater extent than the latter. Possibly because permeability is more easily measured in the laboratory, considerable information is available concerning the variations in permeability. Much of this information would be useful in both qualitative and quantitative determinations of the infiltration rate if only a suitable analysis relating these parameters were available.

The relative simplicity of one dimensional system in general would appear to make the one dimensional saturated surface infiltration system most amenable to such an analysis. In this paper an idealization of such a system is analyzed as an initial step in this direction.

Analysis of one dimensional infiltration—In a previous paper [*Hall*, 1955] the author derived an equation for the infiltration rate as a function of the distance below the soil surface to which the saturated zone extends. The saturation surface, defined as the surface in the soil on which the pressure of the water is equal to atmospheric pressure, forms the lower boundary of the saturated zone. The infiltration rate is obtained by applying the Darcy equation to this saturated zone.

$$f = K(d + z)/z \tag{1}$$

Where f is the infiltration rate, K is the saturated permeability of the soil, d is the depth of water ponded on the surface and z is the depth of penetration of the saturation surface.

The results of experiments reported by *Bodman* and *Colman* [1943] and by *Miller* and *Richard* [1952] indicate that in the transmission zone next below the saturated zone, the moisture content is very nearly constant and the hydraulic gradient very nearly equal to unity. Let the permeability in the transmission zone be K_t. The rate at which water passes through this zone under the hydraulic gradient of unity is equal to K_t. Consider a small increment of distance Δz just below the position of the saturation surface at time t. The rate of inflow to this increment will be greater than the rate of outflow and the moisture content will be raised from θ_i, the percentage moisture by volume in the transmission zone, to θ_s the moisture content by volume in the saturated zone. The volume available for moisture storage in the increment Δz for unit area is

$$\Delta V = (\theta_s - \theta_i)\Delta z \tag{2}$$

The volume rate at which fluid is accumulating in this increment is equal to the difference between inflow and outflow or

$$\Delta V/\Delta t = f - K_t \tag{3}$$

Combining (2) and (3) gives

$$\Delta z/\Delta t = (f - K_t)/(\theta_s - \theta_i) \tag{4}$$

Eq. (4) may be integrated if it is postulated that (1) the saturated permeability of the soil is constant, (2) the nonsaturated permeability in the transmission zone is constant, and (3) the moisture content in the transmission zone is constant. Although postulate (1) is not always realized because of the swelling of colloids and the effects of microorganisms it is a customary postulate in analyses of saturated flow. Postulate (3) appears to be substantiated by the results of *Miller* and *Richard* [1952]. If we accept the principle that non-saturated permeability is a function of the moisture content, except for hysteresis on wetting up or draining, postulate (2) should not be unreasonably restrictive.

Substitute the value of the infiltration rate from (1) in (4). Set the increment ratio $\Delta z/\Delta t$ equal to dz/dt. Integrating the resultant expression with

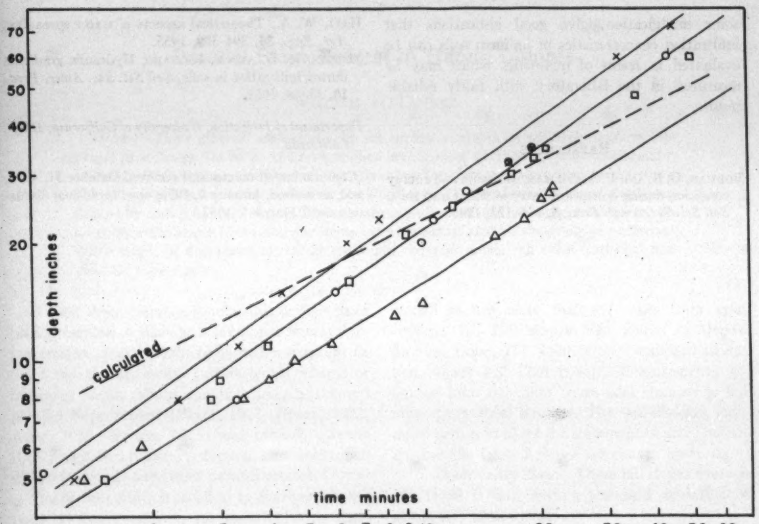

FIG. 1 – Comparison of experimental and calculated position of the wetting front as a function of time; Oso Flaco fine sand

$K \neq K_i$ gives

$$z/(K - K_i) - Kd/(K - K_i)^2$$

$$\log (Kd + Kz - K_iz) = t(\theta_s - \theta_i) \quad (5)$$

For $K = K_i$

$$z = \sqrt{2Kid/(\theta_s - \theta_i)} \quad (6)$$

In a great many instances K_i is approximately equal to K, hence by substitution of (6) into (1) the infiltration rate as a function of time under the conditions stated above is

$$f = K + \sqrt{Kd(\theta_s - \theta_i)/2t} \quad (7)$$

Experimental results—Figure 1 shows the results of an experiment in which conditions were kept as nearly as possible to those required in the derivation of (6). A three-inch diameter aluminum pipe, 27 ft long, was filled with Oso Flaco fine sand, placing the sand as carefully as possible. This soil contains no clay hence avoids changes in permeability due to this cause. The infiltrate was treated with $HgCl_2$ at toxic concentrations to prevent problems of microorganisms. The advance of the saturation surface was noted as a function of time. Care was taken that the wetting front did not reach the bottom of the pipe until after the data were obtained.

The average exponent for the experimental problem was 0.6 while the theory predicts 0.5. The parallel displacements of the curves are probably due to changes in permeability occasioned by removing and replacing the sand. The sand was removed between runs 1, 2, and 3 but was not removed between 3 and 4. No means of obtaining saturated and transmission-zone moisture contents was available, but other experiments with the same soil indicate this difference is approximately 0.20. The permeability of this soil has been measured as 1.2 cm/min. These values are used in (6) to compute a theoretical infiltration curve which is also plotted in Figure 1 for comparison purposes.

Summary—Equations have been developed, under somewhat restrictive hypotheses, which establish a relationship between the permeability of the soil, the moisture characteristics, and the infiltration rate as a function of time. Experimental observations under conditions as near as possible to those of the hypothesis show a reasonably fair agreement for the soil used in the experiment. These equations, although not necessarily applicable to more complex field situations without

some modification, give good indications that infiltration characteristics of uniform soils can be evaluated in terms of quantities which may be measured in the laboratory with fairly reliable results.

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Parallel Slope Retreat in Humid Climate

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Abstract—Three different statistical tests are applied to slopes on relatively uniform lithologies in northern Alabama. The tests applied are: Student's t, the correlation coefficient r, and analysis of variance. One hundred forty-five slope measurements were available for study. The following conclusions are drawn for the study area: (1) streams in V-shaped valleys are flanked by convex-upward slopes; (2) slopes above pediments, valley strips, or floodplains are lower than the slopes above actively downcutting streams; and (3) slopes above pediments, valley strips, or floodplains retreat at essentially constant angles. All three statistical tests yield the same results.

At least three different geometrical devices have been presented to show how hill slopes retreat during erosion. *Davis* [1930] published a diagram to point out the distinctive nature of his scheme of declining slopes. Many scientists have advocated parallel slope retreat [*Penck*, 1927; *Bryan*, 1922; *King*, 1953; *Horton*, 1945; and others]. *Lawson* [1932] suggested parallel reduction, a process which differs in details only from parallel retreat.

The present study is an effort to discover in what manner slopes retreat, on essentially constant lithology, in a humid region. One hundred forty-five slopes were measured on USGS-TVA maps (1:24,000; contour interval, 10 or 20 ft. of northern Alabama. The annual precipitation in the region exceeds 50 inches. Eight quadrangles were studied: Doran Cove, Farley, Hollytree, Lim Rock, Maysville, Moontown, Paint Rock, and Scottsboro. All of these except Doran Cove have sides or corners in contact with each other. These eight quadrangles represent a region of more than 1300 sq mi, covered by 28 maps at the same scale (1:24,000).

The regional structure is relatively simple. The outcropping rocks are Mississippian and Pennsylvanian limestones, shale and sandstones having essentially flat dips. The Mississippian shales (Pennington formation) and the Pennsylvanian shales and sandstones (Lee group) crop out on the hill tops. Hill side and valley floor slopes have been cut largely on Mississippian limestones ('Bangor' sequence). The relief in any one quadrangle is about 1000 ft.

The slopes of the region may be placed in four classes (see Fig. 1):

(1) Upland slopes. These were not examined because it was thought that they are not pertinent to the study.

(2) V-shaped valley slopes. Two sub-classes were recognized: (a) Hill slopes immediately above streams. Average slope, 22° (2150 ft/mi); standard deviation, 3° (281 ft/mi). Measurements extended to not more than 0.2 miles from axial streams. (b) Hill slopes high above 2a slopes. Average slope, 17° (1620 ft/mi); standard deviation, about 2.5° (226 ft/mi). Measurements extended from 0.3 miles from axial streams to 0.5 miles from axial streams. The sub-division indicated here is in effect the statement of an hypothesis that the Class 2 slopes are convex upward.

(3) Open valley slopes. These hill slopes average 14° (1380 ft/mi), with a standard deviation of about 2.5° (248 ft/mi).

(4) Lowland slopes. The lowland slopes are wet-climate, open-basin pediments [*Tanner*, 1955]. They extend from scarp toe to axial stream, at 50 to 100 ft/mi, whereas the stream gradients are generally

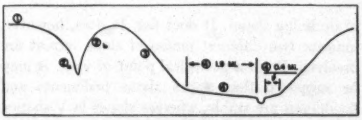

FIG. 1 – Diagrammatic profile showing slope classes (circled) and subclasses

three to 20 ft/mi. Class 3 was also subdivided into subclasses, the latter being labelled according to the distance from the scarp toe to the axial stream. Sub-classes were recognized from 0.0 to 2.5 miles (see Fig. 1).

The first test involved a comparison among slopes of Classes 2a, 2b, and 3 (0.0). The data are summarized in Table 1.

It will be seen, from the values for Student's t, that three distinct populations are compared in this summary. It is concluded that: (1) Classes 2a and 2b are based on a real distinction, and that the V-shaped valley slopes are actually convex upward; and (2) Class 3 (0.0) slopes, that is, slopes above floodplains and pediments, are actually lower than slopes in V-shaped valleys. At first glance it might appear that such a test supports the Davis concept

TABLE 1 – *Student's t test*

Item	Class		
	2a	2b	3(0.0)
n	12	8	22
$\bar{x}$	2150 (ft/mi)	1620	1380
σ	281 (ft/mi)	226	248
ν	18	...	
t	4.24	...	
99.9 pct significance level of t	3.922	...	
ν	...	28	
t	...	2.34	
98 pct significance level of t	...	2.467	
95 pct significance level of t	...	2.048	
ν		32	
t		7.9	
99.9 pct significance level of t		3.60	

TABLE 2 – *Correlation coefficient comparison*

Quadrangle	n	r^2	Change related to distance
			pct
Farley	10	0.114	11
Moontown	20	0.103	10
Lim Rock	20	0.086	09
Doran Cove	15	0.065	06
Scottsboro	20	0.048	05
Maysville	20	0.031	03

of declining slopes. It does not. It does, however, indicate two different modes of slope retreat are involved. From a geological point of view, it may be suggested that slopes above pediments and floodplains are stable, whereas slopes in V-shaped valleys are unstable and hence are maintained at steeper angle. This contrast can be investigated further.

The correlation coefficient r was used to compare Class 3 slopes with distances of toe from axial stream, for six quadrangles. The results are summarized in Table 2.

These measurements include the following subclasses: 0.0 and 0.1 miles, 22 measurements; 0.4, 0.5, 0.6 miles, 34 measurements; 0.9, 1.0, 1.1 miles, 15 measurements; 1.4, 1.5, 1.6 miles, 5 measurements; 1.9, 2.0, 2.1 miles, 9 measurements; and 2.4, 2.5, 2.6 miles, 2 measurements. The conclusion drawn is that Class 3 slopes (above pediments or floodplains) in the study region have relatively stable values, and do not decline or become gentler as they retreat.

To investigate this concept further, Student's t test was applied to three of the sub-classes (Table 3). It is assumed, therefore, that the three sub-

TABLE 3 – *Student's t test of sub-classes*

Item	Sub-class			
	0.0, 0.1 mi	1.4, 1.5, 1.6 mi	1.9, 2.0, 2.1 mi	
n	22	5	9	
$\bar{x}$	1380 (ft/mi)	1370	1280	
σ	248 (ft/mi)	277	234	
ν	25	...		
t	0.076	...		
53 pct significance level of t	0.080	...		
ν	...	29		
t	...	0.998		
85 pct significance level of t	...	1.055		
80 pct significance level of t	...	0.854		

TABLE 4 – *Analysis of variance*

Item	Amount of variation	Degrees of freedom	Estimated variance
Total	473.51	86	5.51
Between columns	46.19	5	9.24
Within columns	427.32	81	5.28

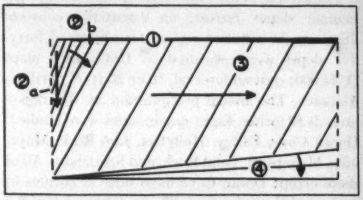

FIG. 2 – Diagrammatic profile showing the sequence of development of slope classes (circled) and subclasses, based on the findings here reported

classes are not significantly different, and that Class 3 slopes do not decline as they retreat.

One additional test was undertaken (Table 4). Analysis of variance was calculated for the following Class 3 slopes: 0.0–0.1, 0.4–0.6, 0.9–1.1, 1.4–1.6, 1.9–2.1, and 2.4–2.6 miles. Eighty-seven measurements were chosen, by sub-class limits, from a total of 105 measurements from six quadrangles. To simplify calculations, each slope value, in feet per mile, was decreased by 1000 and then divided by 100. The F test (9.24/5.28) yielded $F = 1.75$. This is outside the range of significance of published tables, which give: $F = 4.65$ at 99.9 pct; $F = 3.25$ at 99 pct; and $F = 2.33$ at 95 pct. Calculation of an F curve suggests a reading of $F = 1.75$ at 85 pct. Therefore it is believed that there is no real difference between columns (sub-classes), and hence no change in slope with retreat.

It is concluded that for the study area (see Fig. 2):

(1) As V-shaped valleys deepen, the lower slopes (near the axial streams) are maintained at higher angles, while the upper slopes begin to decline toward gentler angles.

(2) When pediment or floodplain first appears, even the lower hill-side slopes are changing from steep angles to lower angles.

(3) After a stable slope has been established above pediment or floodplain, it retreats at a roughly constant angle (provided no changes are made in controlling factors such as lithology, dip, fracture density).

An examination of the eight topographic sheets listed above reveals that in certain instances open-valley slopes are locally oversteepened by stream undercutting (Class 5 slopes). Such cases are obviously local, do not represent the general situation, and should not be included in any of the first four classes.

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Great Earthquakes 1896–1903*

B. GUTENBERG

Abstract—Trace amplitudes of surface wave maxima recorded by undamped Milne seismographs can be used to determine the magnitude of large shallow earthquakes. Magnification of these instruments for maxima of distant shocks was about 5. Station corrections are calculated. Milne's reports and other information are used to find the unified magnitude m and energy E of great earthquakes 1896 to 1903. From 1896 to 1906 the average annual energy release was about 2×10^{25} ergs contrasted with about 0.6×10^{25} ergs from 1907 to 1955. The greatest energy release in any calendar year since 1896 was 5×10^{25} ergs in 1897 that included the great Indian earthquake, one shock off northeast Honshu, and two in the Philippine Islands, all with $m = 8\pm$ and E about 10^{25} ergs. The same order of energy was released in at least one of the Sanriku earthquakes of 1896. The Yakutat Bay shocks of 1899 and 1900 included one with m of $7.9\pm$ and two with $7\frac{3}{4}\pm$. The greatest shock, 1896 to 1955, was possibly the one off Colombia-Ecuador on January 31, 1906, $m = 8.1$ to 8.2, $E = 2 \times 10^{25} \pm$ ergs. The smallest energy release from shallow shocks in any calendar year since 1896 was about 10^{24} ergs in 1954 (when in no shallow shock m exceeded 7.2, though one shock at a depth of nearly 200 km had $m = 7.4$).

Introduction—In their book, *Gutenberg* and *Richter* [1954] began a systematic listing of earthquakes with those of the year 1904. The determination of epicenters, focal depths and magnitudes for shocks of earlier date was considered to be too inaccurate. However, the high seismic activity about the turn of the century makes it highly desirable to find the approximate energy release in earthquakes for years preceding 1904. Fortunately, readings obtained from undamped Milne seismographs [*Milne*, and others, 1895–1911; 1900–1904] are found to permit fairly accurate calculation of energy release in shallow shocks beginning with the year 1896; however, data for shocks originating deeper than about 60 km prior to 1904 are far too scanty for statistical study. In a few instances, unusually great shaken areas indicate the probability of greater focal depth, and for 1903, a few remarks in the bulletins of Göttingen [*Linke*, 1903; *von dem Borne*, 1904], and incidental reproduction of seismograms, permit more definite conclusions.

Materials and methods used—In previous research, reported amplitudes and times based on records of undamped Milne seismographs have also been used. For a study of times and amplitudes measured on records of such instruments Tillotson has kindly furnished the circulars published by *Milne* and others [1900–1904] which cover readings beginning late in 1898, and similar earlier data, starting with 1896, which are contained in *Milne* and others [1895–1911]. Both series contain reproductions of selected seismograms. Other collections of essential data used have been published by *Rudolph* [1903ab], *Tams* [1908], and, for Japan only, *Rudolph* [1904b], *Anon.*, [1952], and *Szirtes* [1912?]. Station bulletins available here, some with data from other stations or macroseismic reports, include *Anon.* [1931], *Kortazzi* [1900], *Levitsky* [1903, 1904], *Linke* [1903], *Schütt* [1900], and *von dem Borne* [1904]. Most macroseismic data are based on *Milne* and others [1895, 1900], *Milne* [1911], *Rudolph* [1905], and *Sieberg* [1932]. For additional references, see *Gutenberg* and *Richter* [1954].

By using 16 earthquakes (1904 to 1907) for which magnitudes had previously been determined it was found that undamped Milne instruments had an average magnification of about 5 for maximum waves with periods of the order of 20 seconds. Average 'station corrections' based on the same shocks are listed in Table 1. These corrections have to be added to the unified magnitude m [*Gutenberg* and *Richter*, 1956; *Gutenberg*, 1956] calculated from the ground amplitudes of surface wave maxima in microns (200 times the reported maximum trace amplitudes of Milne seismographs in mm), for example, by use of Figure 2 in *Gutenberg* and *Richter* [1956]. It is assumed (from reproduced seismograms probably with rare major errors) that these maxima have periods of roughly 20 seconds. The magnitude M used formerly is connected with the unified magnitude m approximately by

$$M = 1.59\, m - 4.0 \qquad (1)$$

An example of the unexpectedly small scatter

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TABLE 1 – *Station corrections for magnitude calculations from Records of undamped Milne instruments 1904–1907*

Station	Cor.	Station	Cor.
Azores	+0.2	Kew	−0.1
Baltimore	0.0	Kodaikanal	+0.1
Batavia	0.0	Malta	0.1
Bombay	0.0	Mauritius	0.0
Bidston	0.0	Paisley	0.0
Beirut	+0.1	Perth	+0.2
Calcutta	−0.1	San Fernando	−0.1
Capetown	+0.2	Shide	−0.1
Christchurch	0.0	Sydney	+0.2
Cheltenham	0.1	Tokyo	+0.2
Colombo	0.0	Toronto	+0.2
Cordoba	+0.2	Tiflis	0.0
Edinburgh	0.0	Trinidad	+0.1
Haslemere	−0.2	Victoria	+0.2
Helwan	+0.1	Vieques	−0.2
Honolulu	0.0	Wellington	+0.1
Irkutsk	0.0		

TABLE 2 – *Unified magnitude m of the San Francisco earthquake, April 18, 1906, based on reported maximum amplitudes of undamped Milne seismographs, on the assumption of a magnification of 5 and the corrections in Table 1*

Station	Distance	Ground motion maximum	m
	°	micron	
Shide	77°	4000	7.8
Azores	73	1460	7.8
Calcutta	113	3400	7.9
Bombay	121	1200	7.8
Kodaikanal (Madras)	128	500	7.7
Batavia	125	600±	7.6±
Helwan	108	900	7.7
Trinidad	61	2000	7.7
Perth	132	550	7.8
Wellington	95	1800	7.9
Tokyo	73	900	7.7
Christchurch	100	1360	7.7
Colombo	120	1500	7.9
Mauritius	162	1000	7.8
Kew	75	≥3400	≥7.7
Bidston	75	beyond paper	...
Edinburgh	73	≥3400	≥7.8
Paisley	75	≥3400	≥7.8
San Fernando	85	≥3500	≥7.8
Toronto	33	≥4000	≥7.7
Irkutsk	81	≥3400	≥7.9
Average	...	...	7.8

of magnitudes calculated from reported trace amplitudes of undamped Milne instruments is given in Table 2 for the San Francisco earthquake of 1906. Their average $m = 7.8$ agrees with the value $m = 7.7$ ($M = 8\frac{1}{4}$ of the old scale) calculated previously from 15 maxima recorded by more modern, damped instruments. Similar good agreement was obtained for other great earthquakes. From all reported data available here (including Milne's) and reproduced seismograms it was found that the magnitude m of the earthquake off Colombia-Ecuador on January 31, 1906, was 8.1 to 8.2. The only other shock between 1897 and 1955 for which a magnitude as great as 8.1 has been found occurred on March 2, 1933, off the Sanriku coast of Honshu.

Great shallow shocks, 1897 to 1903—Table 3 contains all shocks 1897 to 1903 for which a unified magnitude m of 7.4 or more (corresponding to the earlier $M \geq 7\frac{1}{4}$) has been found. In the column marked Q, the following letters (similar to those in *Gutenberg* and *Richter*, [1954, p. 11]) are used to indicate the estimated limits of error in the epicenter locations:

A	B	C	D	E	F	G
±1°	±2°	±3°	±5°	±10°	±20°	>20°

For the period 1899–1903, probably no shallow shock with m over 7.3 is missing, except for borderline cases, and most listed magnitudes are considered to be accurate at least within ±0.2 units. Unfortunately, for 1899 to 1903 the locations of earthquakes based on microseismic data alone are usually uncertain by at least 5° and in many instances larger errors must be expected. This is partly because the magnification of the Milne instruments was frequently too low to record the *P*-phases, and that consequently the earliest reported time often refers to *S* or even a later phase. Moreover, during these years the various phases and their travel times were very poorly known, many observers were interested mainly in the surface waves, and at some stations, clock corrections seem to have been frequently in error by several minutes. As a consequence, Milne sometimes determined two or three epicenters from records pertaining to one single shock [see, for example, *Milne*, 1895–1911, 16th Report for 1911, p. 6 of reprint].

In the present paper the assumption has repeatedly been made that an epicenter was in one of the major earthquake belts. However, even for shocks during the years 1899 to 1903 it was occasionally not possible to discriminate between epicenters in the New Hebrides belt and those in the Tonga belt. No epicenter listed in Table 3 can be used to determine the seismicity in a limited region unless it is corroborated by macroseismic results.

For the years 1897 and 1898 listing is probably complete for shocks of magnitudes m over $7\frac{1}{4}$.

TABLE 3 – *List of great earthquakes 1897 to 1903*

Date	O	Epicenter				Region in which shock was felt or destructive	m	E
		Lat.	Long.	Q	Region			
	hr	°	°					
1897								
Feb. 7	7.6	40 N	140 E	C	Japan	NE Honshu	7¾±	2.5
Feb. 19	20.8	38 N	142 E	C	Japan	NE Honshu	7¾±	2.5
Feb. 19	23.8	38 N	142 E	C	Japan	NE Honshu	7½±	0.6
May 13	12.5	12 N	124 E	D	Philippine Is.	Masbate	7½±	0.6
June 12	11.1	26 N	91 E	A	India	Assam	8	10
Aug. 5	0.2	38 N	143 E	C	Japan	NE Honshu	8	10
Aug. 15	12.3±	18 N	120 E	D	Philippine Is.	Luzon	7½?[a]	0.6?
Aug. 16	7.9	39 N	143 E	C	Japan	NE Honshu	7½±	0.6
Sep. 20	19.1	6 N	122 E	D	Philippine Is.	Mindanao to Jolo	7.9±	6
Sep. 21	5.2	6 N	122 E	D	Philippine Is.	Mindanao to Jolo	8±	10
Oct. 18	23.8	12 N	126 E	D	Philippine Is.	Samar, Visayan I.	7.6	1.1
Oct. 20	14.4	12 N	126 E	D	Philippine Is.	Samar, Visayan I.	7.5	0.6
1898								
Jan. 24	23½	?	?	G	?	no report	7½?	0.6?
Apr. 22	23.6	39 N	142 E	C	Japan	NE Honshu	7¾±	2.5
Apr. 29	16.3	12 N	86 W	B	Nicaragua	Managua, large area	7½±	0.6
June 29	18.6±	?	?	G	Aleutian Is.?	No report	7¾±	2.5
Aug. 31	19.9±	?	?	G	Indian Ocean?	No report	7½±	0.6
Nov. 17	12.8±	?	?	G	SW Pacific?	No report	7.4±	0.4
1899	h m							
Jan. 24	23 43±	17 N	98 W	D	Mexico	Vera Cruz to Oaxaca	7.8±	3.3
June 14	11 09±	18 N	77 W	E	Jamaica	Jamaica	7.4	0.4
July 14	13 32?	?	?	G	Arctic near Alaska	No report	7.4±	0.4
Aug. 24	15 09±	?	?	G	SW Pacific	No report	7.4	0.4
Sep. 4	00 22	60 N	142 W	B	Alaska	W. of Yakutat Bay	7.7	1.9
Sep. 10	17 04	60 N	140 W	B	Alaska	Yakutat Bay	7.4	0.4
Sep. 10	21 41	60 N	140 W	A	Alaska	Yakutat Bay	7.9	5.8
Sep. 29	17 03	3 S	128½E	A	Ceram[b]	Ceram	7.4	0.4
Nov. 23	09 49±	53 N	159 E	E	S. Kamchatka	No report	7.5	0.6
Nov. 24	18 42	32 N	131 E	B	Japan	Kiushiu	7.4	0.4
Nov. 24	18 55	32 N	131 E	B	Japan	Kiushiu	7.4?	0.4
1900								
Jan. 11	09 07	?	?	G	SW Pacific?	No report	7.4?	0.4
Jan. 20	06 33½	20 N	105 W	C	Mexico	Mexico City—Pacific	7.7±	1.9
May 16	20 12	20 N	105 W	D	Mexico	Colima, Jalisco	7.4±	0.4
June 21	20 52	20 N	80 W	F	Caribbean?	No report	7.5	0.6
July 29	06 59	10 S	165 E	F	New Hebrides?	No report	7.6	1.1
Oct. 7	21 04	4 S	140 E	F	New Guinea?	No report	7.4	0.4
Oct. 9	12 28	60 N	142 W	C	Alaska	W. of Yakutat Bay	7.7	1.9
Oct. 29	09 11	11 N	66 W	B	Venezuela	Caracas	7.8	3.3
Dec. 25	05 04	43 N	146 E	C	Japan	E. Hokkaido	7.4	0.4
1901								
Jan. 7	00 29½	2 S	82 W	E	Ecuador	No report	7.4	0.4
Apr. 5	23 30½	45 N	148 E	C	S. Kurile Is.	Nemuro	7.5	0.6
June 24	07 02½	27 N	130 E	E	Riu Kiu Is.	No report	7.5	0.6
Aug. 9	09 23.5	40 N	144 E	C	off NE Honshu	Aomori	7.5	0.6
Aug. 9	13 01	22 S	170 E	E	New Hebrides?	No report	7.8	3.3
Aug. 9	18 33¼	40 N	144 E	C	off NE Honshu	Aomori	7.7	1.9
Dec. 14	22 57¼	14 N	122 E	D	Philippine Is.	Batangas	7.4	0.4
Dec. 31	09 02½	52 N	177 W	D	Aleutian Is.	No report	7.4	0.4
1902								
Jan. 1	05 20½	55 N	165 W	D	Off Alaska?	No report	7.4	0.4
Jan. 24	23 27	8 S	150 E	D	Bismarck Is.	No report	7.4	0.4
Feb. 9	07 35	20 S	174 W	D	Tonga Is.	No report	7.4	0.4
Apr. 19	02 23½	14 N	91 W	C	Guatemala	Guatemala	7.7	1.9
Aug. 22	03 00	40 N	77 E	B	Turkestan	Kashgar	7.9	5.8
Sep. 22	01 46½	18 N	146 E	C	Marianne Is.	No report	7.6	1.1

TABLE 3 – *List of great earthquakes 1897 to 1903 (Continued)*

Date	O		Epicenter				Region in which shock was felt or destructive	m	E
			Lat.	Long.	Q	Region			
	h	m	°	°					
1902									
Sep. 23	20	18½	16 N	93 W	C	Off S. Mexico	Mexico—Guatemala	7.8	3.3
Dec. 12	23	10±	29 N	114 W	E	Gulf of California	No report	7.4	0.4
1903									
Jan. 14	1	47.6	15 N	98 W	D	Off Mexico	Mexico—Guatemala	7.7	1.9
Feb. 1	9	34.5	48 N	98 E	D	SW of Lake Baikal	Taskent?	7.4	0.3
Feb. 27	0	43.3	8 S	106 E	D	East Indies	Sumatra—Java	7.6	1.0
May 13	6	34.1	17 S	168 E	E	New Hebrides	No report (h = 60 ± km?)	7½±	0.6
Dec. 28	2	56.0	7 N	127 E	D	Off Mindanao	Mindanao, Celebes	7.4	0.3

O = origin time; Q = quality of location (see text); m = unified magnitude; E = energy in 10^{24} ergs, calculated from $\log E = 5.8 + 2.4m$, where m is the unified magnitude (see text).

[a] About the same time a shock was reported from Turkestan (Taskent). If the surface-wave maxima in Europe belong to the Turkestan shock, its magnitude was about $m = 7\frac{1}{4}$ and that of the Philippine shock which did damage in northern Luzon and had many aftershocks was less than $7\frac{1}{4}$.

[b] See *Rudolph* [1904a]

Most results are less reliable than those for 1899, but probably few magnitudes in Table 3 are incorrect by as much as ¼. Shide is the only station for which reported amplitudes of a Milne pendulum are available for both years; those for Toronto started in September, 1897. In addition, reports of amplitudes for Kew, Victoria, Madras, Bombay, Batavia, and Mauritius are available for a part of 1898. Seismograms reproduced by Milne could be used as well as trace amplitudes for Nicolajew [*Kortazzi*, 1900] after employing a calibration similar to that described for Milne instruments. The magnification of the Nicolajew instrument for maximum surface waves was roughly 20. To supplement information for the earlier shocks, reported data for trace amplitudes at several Italian, German, and English stations for 1896 to 1898 were compared with similar data for earthquakes of known magnitude in a given region during later years.

For 1896, only rough results for some great shocks could be obtained, mainly by comparison of amplitudes at a few stations as mentioned above. The Milne pendulum at Shide started recording in June; *Rudolph* [1903b, 1904b] has given some amplitudes for shocks in Japan. A systematic collection of data for 1896 and earlier years can not be expected to improve appreciably our knowledge of great shocks, since the first instruments useful for amplitude determination were being developed during this period, and data pertaining to teleseisms exist only for a limited portion of the world. The Reports of the British Association, 1881 to 1895, mainly give data on shocks in Japan and on properties of instruments. Similar and additional information can be found in the *Transactions of the Seismological Society of Japan* starting 1880, in the *Bolletino della Società Sismologica Italiana* starting 1895, and in the early volumes of *Gerlands Beitraege zur Geophysik*.

Following are some remarks concerning shocks of interest not listed in Table 3, and additional information concerning some of the shocks listed:

For 1896, the data for great shocks are very incomplete and all results are tentative. On January 19, 13.3h, a shock off central Honshu had a magnitude of $m = 7.6 \pm$. On March 4, 5h and on May 5, 23h, there were probably great shocks ($m = 7\frac{3}{4}\pm$?) but the information is not sufficient to find even the part of the world where each occurred. On June 15, at 10h, 19h and 23h there were three very destructive shocks off the Sanriku coast. Sanriku is usually not to be found on maps; it means "Three Riku" and combines the provinces of Rikuchu, Rikuzen and Rikuoku of northeast Honshu. For the first and the last of these shocks, and for one on June 17 at 3h which apparently occurred off central Honshu, the Central Meteorological Observatory in Tokyo [*Anon.*, 1952] reports relatively great magnitudes. At least one of these shocks had a magnitude of about $m = 8$ and in two additional, m was probably between $7\frac{3}{4}$ and 8; the same magnitude was probably reached in the second of two shocks on August 31, at 7h and 8h, in the Sanriku region. This very unusual activity [see, for example, *Davison*, 1936, pp. 130–135; *Milne* and others, 1897, pp. 153–158] near the coast of northeastern Honshu

continued with great earthquakes in 1897 and 1898 (Table 3).

In 1897, May 28, 22.6h there was a large shock, possibly at intermediate depth, in the eastern Mediterranean. It was felt from Albania and Malta to the Cyclades. For the great Indian earthquake of June 12 [*Oldham*, 1899] the following magnitudes m were found from reproduced seismograms and reported trace amplitudes: Rocca di Papa, 8.0; Ischia 7.9; Catania 8½ (?); at Shide ($m > 7.8$), and several other stations with relatively insensitive instruments in Europe the record exceeded the width of the paper. On December 29, 11.3h, a destructive shock in Santo Domingo had a magnitude of $m = 7.3$. The complete lack of listed great earthquakes in the southern hemisphere for 1897 and their poor representation for 1898 and 1899 may result, at least in part, from insufficient data.

In 1898, there was a shock on April 15, about 7.2h, with damage along the coast of Mendocino County, California, with a magnitude of $m = 7.1\pm$. The shock in Nicaragua on April 29 was felt or damaging over an exceptionally large area; however, the records reproduced by Milne show large surface waves, and the shock can not have been much deeper than normal.

In 1899, April 12, 17h 24m, there was a destructive earthquake in Rioja and Tucuman, Argentina, near 28°S, 67°W with $m = 7.3$. The Yakutat Bay shocks [*Tarr* and *Martin*, 1912] include the following not listed in Table 3: September 4, 4.7h, $m = 7\frac{1}{4}$; September 7, 12.8h, $m = 7.2$; September 23, 11.1h, $m = 7.3$; and 12.8h, $m = 7.3$. On December 25, 12.5h, a shock destructive near San Jacinto, California, had a magnitude of about $m = 7$.

In 1900, the shock of January 20 in Mexico had an unusually large shaken area and its epicenter is in the belt of shocks with intermediate focal depth. The shock of May 16 was possibly an aftershock.

In 1901, a shock on November 15, 20.2h,

TABLE 4 – *Shallow earthquakes between January, 1904, and July, 1956, for which* $m > 7\frac{3}{4}$

Date	Origin time	Epicenter			m
		Lat.	Long.	Region	
	h m	°	°		
Apr. 4, 1905	00 50.0	33 N	76 E	Kangra, India	7.9
July 9, 1905	09 40.4	49 N	99 E	Mongolia	7.8
July 23, 1905	02 46.2	49 N	98 E	Mongolia	8.0
Jan. 31, 1906	12 36.0	1 N	81½W	Off Colombia–Ecuador	8.1–8.2
Aug. 17, 1906	00 40.0	33 S	72 W	Valparaiso, Chile	7.9
Sep. 14, 1906	16 04.3	7 S	149 E	New Guinea	7.8
Jan. 3, 1911	23 : 25:45	43½N	77½E	Tien Shan	8.0
May 1, 1917	18 26.5	29 S	177 W	Kermadec Trench	7.9±
June 26, 1917	05 49.7	15½S	173 W	Tonga Trench	8.0
	h m s				
Apr. 30, 1919	07 17 05	19 S	172½W	Tonga Trench	7.8
Dec. 16, 1920	12 05 48	36 N	105 E	Kansu, China	7.9
Nov. 11, 1922	04 32.6	28½S	70 W	Atacama, Chile	7.8
Feb. 3, 1923	16 01 41	54 N	161 E	Kamchatka	7.8
Mar. 7, 1929	01 34 39	51 N	170 W	Aleutian Is.	7.9
Mar. 2, 1933	17 30 54	39½N	144½E	Off NE Honshu, Japan	8.1
Jan. 15, 1934	08 43 18	26½N	86½E	Bihar-Nepal, India	7.8
Feb. 1, 1938	19 04 18	5½S	130½E	Banda Sea	7.9
Nov. 10, 1938	20 18 43	55½N	158 W	Off Alaska	8.0
May 24, 1940	16 33 57	10½S	77 W	Peru	7.8
June 26, 1941	11 52 03	12½N	92½E	Andaman Is.	8.0
Nov. 25, 1941	18 03 55	37½N	18½W	Atlantic, off Portugal	7.8
Aug. 24, 1942	22 50 27	15 S	76 W	Off Peru	7.9
Dec. 20, 1946	19 19 05	32½N	134½E	Nankaido, Japan	7.8
Aug. 15, 1950	14 09 30	28½N	96½E	Tibet	8.0
Mar. 4, 1952	01 22 43	42½N	143 E	Hokkaido, Japan	7.9
Nov. 4, 1952	16 58 26	52½N	159½E	Kamchatka	7.8

destructive at Cheviot on the South Island of New Zealand, had a magnitude of about 7½.

In 1903, at 5.5h on January 24 a shock damaging in Lower California near 31½°N 115°W had a magnitude of about $m = 7$. A shock of magnitude $m = 7$ on October 21, 9h57m, was the earliest known of the series near 34°S, 52°E in the Indian Ocean. The following shocks occurred at intermediate or great focal depth: on January 4, 5h7½m, $m = 7\frac{1}{2}$ to $7\frac{3}{4}$, near 20°S, 175°W in the Tonga sector; on June 2, 13h17m, $m = 7\frac{1}{2}\pm$, near 57°N, 156°W (Alaska) probably at intermediate depth; on August 11, 4h32.9m, depth 100 to 150 km, $m = 7\frac{1}{4}$, in the eastern Mediterranean near 36°N, 23°E; on October 19, at 3h06.0m, depth probably somewhat over 200 km, $m = 7$ to $7\frac{1}{4}$ under the Hindu Kush.

Since the unified magnitude m for individual earthquakes has not yet been published, shallow shocks with m exceeding $7\frac{1}{4}$ between January, 1904 and April, 1956 are listed in Table 4.

Energy release since 1896—The energy release by earthquakes calculated previously [*Gutenberg*, 1956] for each of the years 1904 to 1954 can now also be found for the years 1896 to 1903, though less accurately for 1896 to 1898. The equation connecting the energy E and the magnitude m is [*Gutenberg* and *Richter*, 1956]

$$\log E = 5.8 + 2.4\, m \qquad (2)$$

giving the following corresponding values of m and E (in ergs):

m	8.1	8.0	7.9	7.8	7.7	7.6
E	17.4	10.0	5.8	3.3	1.9	1.1
m	7.5	7.4	7.3	7.2	7.1	7.0
E	0.6	0.4	0.2	0.1	0.07	0.04×10^{24}

Eq. (2) gives values of log E which are probably correct within one unit, if $m < 7.7$; its accuracy for $m > 7.6$ has to be investigated as soon as data are available. Moreover, an error of 0.1 in m for one shock with $m \geq 8.0$ affects the total energy for a year more than omission of several shocks of magnitude below 7.8. Thus, the total energy for the year 1896 depends more on the exact magnitude of the Sanriku earthquakes than on omitted shocks of magnitudes below 7.8.

From results of *Gutenberg* [1956] the following approximate average energy E^* released in one year in all shallow shocks of magnitudes up to and including m^* has been found:

m^*	7.0	7.1	7.2	7.3	7.4	7.5
E^*	0.5	0.7	1.0	1.3	1.7	2.2×10^{24} ergs

Again, the errors in E^* are smaller than errors in E resulting from incorrect determination of m for the largest shocks. Table 5 gives the calculated energy release in shallow shocks during each of the years 1896 to 1955. For 1896 to 1903 it is based on the data in Table 3 and the preceding tabulation of E^*, for years following 1903 on *Gutenberg* [1956]. The resulting accumulated energy release in shallow shocks since 1896 is plotted in Figure 1.

TABLE 5 – *Annual energy release E in shallow earthquakes in 10^{24} ergs*

Year	E	Year	E	Year	E	Year	E
1896	30±	1910	1.9	1925	2.2	1940	4.4
97	47	11	13.6	26	2.6	41	16.1
98	9	12	2.5	27	3.6	42	13.4
99	17	13	4.4	28	5.6	43	8.3
		14	1.9	29	9.2	44	4.9
1900	12	1915	3.0	1930	1.1	1945	3.5
01	10	16	3.6	31	5.4	46	8.6
02	16	17	18.7	32	4.7	47	3.0
03	6	18	7.9	33	19.0	48	5.2
04	10.6	19	6.0	34	6.6	49	3.8
1905	22.2	1920	11.1	1935	3.6	1950	14.4
06	34.1	21	1.1	36	2.6	51	2.2
07	4.9	22	5.2	37	1.7	52	11.3
08	1.9	23	6.9	38	19.0	53	4.0
09	1.9	24	4.9	39	5.1	54	0.9
						55	1.3

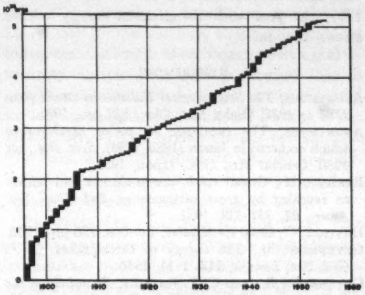

FIG. 1 – Accumulated yearly energy release in shallow shocks

Between 1896 and 1906 the average annual energy released in shallow shocks was about 2×10^{25} ergs, which is about three times the annual average of 0.6×10^{25} ergs during 1907 to 1955. To find the corresponding strain release, the square roots of the energies for each significant shock have to be taken. For great shocks, *Benioff* [1951] found quasi-periodic changes of strain release. Years, in which according to his results a period

of greater strain release started, are indicated in Table 4 by a preceding line.

There seem to be no answers yet to the following questions: What caused the rather sudden decrease in seismic activity in 1907? Does the energy release follow a cycle? Was the energy release unusually great before 1907? Or has it been unusually small since 1907? For tectonic problems most of the answers are not significant, since the period covered by Figure 1 is extremely small on the geological scale. However, for protection against earthquake damage, the answers could be highly important. The heat released in radioactive processes in the interior of the Earth, which probably furnishes ultimately the energy released in earthquakes, corresponds roughly to 10^{28} ergs annually and thus probably could support an even larger rate of energy release in earthquakes than that of 2×10^{25} ergs prevailing in the average between 1896 and 1906, or that of 5×10^{25} ergs found for 1897, the year with the greatest energy release known thus far.

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Velocity of Lg Waves in California*

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Abstract—It is of interest to establish whether or not the crust is anomalous in orogenic belts. The velocity of Lg waves for paths traversing orogenic belts in California differs by less than two per cent from velocities found for transcontinental paths. These results suggest that the velocity of shear waves in the upper part of the continental crust is uniform, but do not necessarily imply homogeneity of materials that make up the crust.

Introduction—The earthquake phase Lg is a short-period surface wave which is propagated through the silicic crust of continents [*Press* and *Ewing*, 1952]. It is characterized by: (1) Sharp commencements with periods in the range $\frac{1}{3}$ to 5 seconds. (2) Predominantly transverse horizontal motions but with significant transverse vertical motions present. (3) Propagation with little attenuation, resulting in amplitudes large compared to those of any other phase in the same period range. (4) Rapid extinction by propagation over a segment of as little as 100 km of oceanic crust. (5) Velocity of propagation variously reported at 3.51 km/sec [*Press* and *Ewing*, 1952], 3.57 km/sec [*Lehmann*, 1953], 3.54 km/sec [*Båth*, 1954], and 3.60 km/sec [*Gutenberg*, 1955a]. (The 3.57 and 3.60 values are not strictly comparable with the others in that the authors have allowed for an intercept in the Lg travel time curve.) This is essentially the velocity of shear waves in the upper part of the silicic crust of continents. (For a summary of shear wave velocities, see Gutenberg [1955b, p. 23].)

The Lg phase has been used to establish the elastic uniformity of large segments of the continental crust. *Ewing* and *Press* [1955, p. 2] pointed out that the variation in velocity for numerous paths in North America, Eurasia, and Africa, ranging up to several thousand kilometers in length is less than two per cent. A major part of even this small variation may safely be ascribed to uncertainties in epicenter location.

It is of considerable interest to determine whether or not the crust is anomalous in orogenic belts. This information is important not only for our understanding of the mechanism of orogeny. It is essential for the proper interpretation of variations in phase velocity of surface waves [*Press*, in press]. The Lg phase provides the means for examining one elastic parameter, the shear velocity in the upper part of the continental crust. The procedure is to compare Lg velocities for paths crossing orogenic belts with velocities determined for transcontinental paths.

The greatest source of error in Lg velocity determinations is uncertainty in epicentral data. This error increases with decreasing propagation paths. To determine with sufficient precision the Lg velocity for the relatively short paths required to traverse the length of an orogenic belt a greater accuracy in epicentral data is required than is usually available. This accuracy can be achieved for local earthquakes in California because of the high density of good quality seismograph stations. Moreover, the distribution of stations and epicenters allows for paths traversing the length of the major structural features of California.

The data—The basic data for this study were derived from northern California and Nevada earthquakes reported in the Bulletin of the Seismograph Stations of the University of California and the Kern County earthquakes of 1952 studied by *Richter* [1955]; Lg waves were identified on seismograms of the Berkeley and Pasadena groups of stations. The earthquakes and stations are listed in Table 1 together with Lg travel times, propagation distances and velocities. A few examples of Lg phases are reproduced in Figure 1. The propagation paths are indicated on a geomorphic map of California in Figure 2.

The mean Lg velocity determined for all the paths shown in Figure 2 is 3.54 ± 0.02 km/sec. The mean velocity for paths traversing the length of the Sierra Nevada block is 3.53 ± 0.02. For the composite paths including the Central Valley and Coast Ranges the velocity is 3.55 ± 0.03 km/sec.

Discussion—Lg velocity determinations for paths traversing the Sierra Nevada or the Central Valley and Coast Ranges differ by less than two

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TABLE 1 – *Lg velocity data*

Date	Origin time			Lat.		Long.		Mag.	Station[a]	Lg tt	Δ	Lg vel.
	h	m	s	°	′	°	′			sec	km	km/sec
Nov. 14 50	02	35	50	40	29	121	30	4.6	C.L.	171	622.4	3.64
	02	04	40	40	29	121	30	4.6	C.L.	172	622.4	3.62
Dec. 14 50	13	24	19	40	05	120	04	5.6	P	194	679.8	3.50
	13	24	19	40	05	120	04	5.6	H	141	476.2	3.38
	13	24	19	40	05	120	04	5.6	R	212	717.0	3.38
	08	59	34	40	05	120	04	4.5	P	193	679.8	3.52
	08	59	34	40	05	120	04	4.5	H	137	476.2	3.48
	08	59	34	40	05	120	04	4.5	R	201	717.2	3.57
Dec. 29 48	12	53	28	39	33	120	05	6.0	P	168	623.2	3.71
	12	53	28	39	33	120	05	6.0	H	120	423.2	3.53
	12	53	28	39	33	120	05	6.0	R	182	662.3	3.64
Sep 26 53	03	34	29	39	32	119	59	5.3	P	176	619.1	3.52
	03	34	29	39	32	119	59	5.3	R	190	657.4	3.46
	03	34	29	39	32	119	59	5.3	T	95	315.0	3.32
	03	34	29	39	32	119	59	5.3	H	125	417.3	3.34
	03	34	29	39	32	119	59	5.3	B.B.	193.5	648.2	3.35
Oct. 26 52	11	36	40	40	05	120	46	4.3	P	200	697.8	3.49
	11	36	40	40	05	120	46	4.3	H	141	502.2	3.56
	11	36	40	40	05	120	46	4.3	T	109	402.4	3.69
Mar. 22 53	05	19	00	38	49	119	59	5.0	H	96	346.9	3.61
	05	19	00	38	49	119	59	5.0	R	162	584.1	3.61
Nov. 14 51	08	39	53	40	26	124	03	4.7	P	239	870.8	3.64
	08	39	53	40	26	124	03	4.7	C.L.	211	763.5	3.62
July 23 52	07	37	00.2	35	17	118	33	4.8	S.F.	124	443.3	3.58
	13	13	08.6	35	19	118	30	5.0	S.F.	123	444.5	3.61
July 22 52	08	47	34.3	35	05	118	45	4.7	S.F.	124	444.1	3.58
	08	47	34.3	35	05	118	45	4.7	Reno	139	503.3	3.62
July 23 52	04	01	39.6	35	22	118	35	4.7	S.F.	124	435.2	3.51
July 31 52	04	10	21.7	35	17	118	33	4.2	Reno	138	485.1	3.52
July 31 52	19	53	14.0	35	20	118	55	4.5	Reno	131	473.3	3.61
July 31 52	19	05	14.8	35	19	118	30	4.0	Reno	138	482.6	3.50
Aug 22 52	22	41	23.8	35	20	118	55	5.8	Arcata	210	763.9	3.64
Aug 23 52	10	09	07	34	30	118	13	5.0	M.H.	129	441.5	3.42
	10	09	07	34	30	118	13	5.0	Palo Alto	142	481.2	3.39

[a] C.L., China Lake; P, Pasadena; H, Haiwee; R, Riverside; T, Tinemaha; B.B., Big Bear; S.F., San Francisco; M.H., Mt. Hamilton.

per cent from the values reported for transcontinental North American and Eurasian paths. This strongly suggests that the shear velocity in the upper part of the continental crust is not anomalous in orogenic belts. This does not necessarily imply homogeneity of materials that make up the crust but rather as *Birch* [1955, p. 104] suggests, a uniformity in seismic velocity of the materials.

The local phase velocity of Rayleigh waves depends upon the period, the thickness of the crust, and the elastic constants of the crust and mantle. The uniformity of shear velocity in the upper

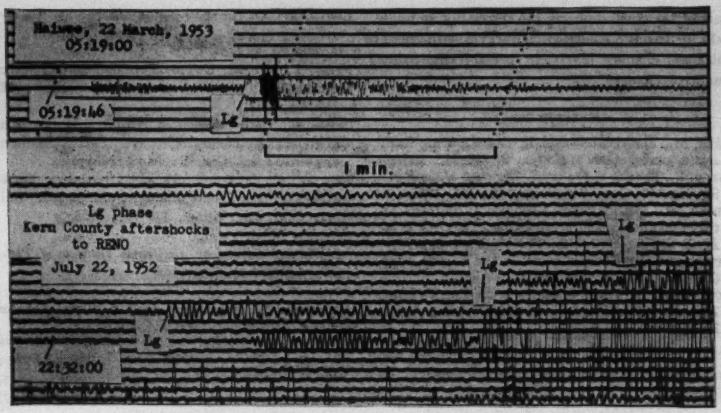

FIG. 1 – Examples of Lg phases for California paths

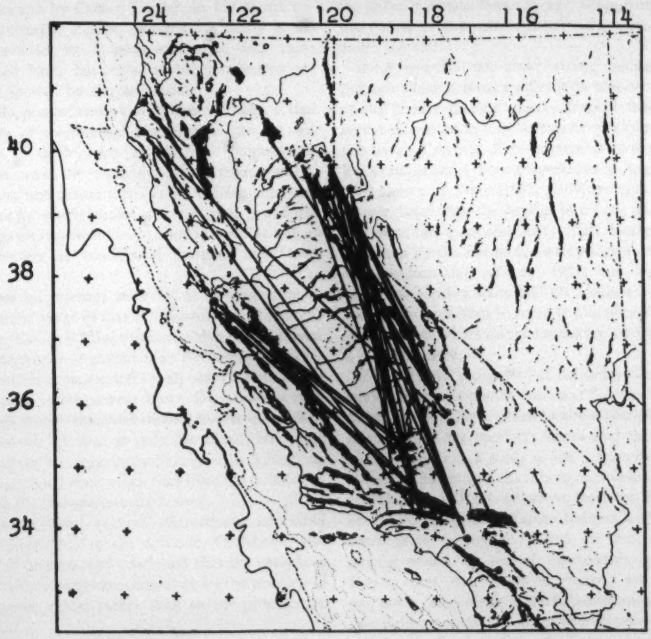

FIG. 2 – Paths traversed by Lg waves used in velocity determination

part of the crust supports the correlation of phase velocity variations of Rayleigh waves with crustal thickness changes [*Press*, in press] rather than elasticity changes.

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Microseisms with Periods of Seven to Ten Seconds Recorded at Bermuda*

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Abstract—Three years of Milne-Shaw seismograms from Bermuda were examined and, in certain cases, compared to seismograms from Palisades. Thirty-four periods of time were found during which Bermuda recorded storms of 7–10-sec microseisms. It is shown that weather conditions along the east coast of North America are the source of these microseisms in all cases except one. This one 7–10-sec microseisms storm is correlated with an intense low pressure area in the north Atlantic northeast of Bermuda. These 7–10-sec microseisms are related to short period surface waves from earthquakes, and it is shown that the continental margin acts as a barrier to propagation.

This study depends largely on data from two Milne-Shaw horizontal seismographs at the Bermuda-Columbia Seismograph Station at St. Georges, Bermuda. They are oriented NW-SE and NE-SW, have free periods of about 12 sec and magnification of about 250. Earlier studies of Bermuda microseisms have been made by Donn and coworkers and by Carder. Carder, in his recent papers, [including *Carder*, 1955b] gives many observations which are in good agreement with those reported here, but some of his conclusions are not supported by the new data.

In the present study the fundamental idea is that aspects of microseism transmission can be observed in earthquake surface wave propagation. This removes the microseism waves from a special category and relates them to waves from impulsive sources for which studies of group velocity and dispersion for continental and oceanic paths as well as attenuation at continental margins have been made.

Most microseisms recorded at Bermuda are in the period range of four to five seconds. In a recent paper, *Carder* [1955a] attributes these microseisms to cold fronts or storms near Bermuda, a conclusion which is supported by all observations made incidental to the present study. Disturbances with periods shorter than four seconds are recorded when the storms are near or over the island, but these recordings are apparently disturbed by vibrations of a tall signal mast which rises from the building in which the instruments are housed.

Donn [1954a] studied microseisms associated with hurricanes in the Atlantic, Caribbean, and Gulf of Mexico, and concluded that the periods of microseisms depended primarily on the position of the storm center rather than on the propagation paths from the storm center to the recording station, and that when the hurricanes were in certain areas the periods were slightly longer than average. One of these areas is that generally southeast of Bermuda. Another is that south of the continental shelf of Newfoundland, and the third is just north of the West Indian Arc. These being areas where the water is deeper than average, Donn correlated the period of the microseisms with water depth under the storm.

Local weather can make strong microseisms, through which it is very difficult to observe microseisms from a distant source. Even if there is a period difference in microseisms originating in the two areas, they are often impossible to separate. For example the 4–5-sec microseisms of August 17, 1950 shown by *Donn* [1952, p. 69] perhaps should be associated with the passage of a front near Bermuda or the quasi-stationary front located over Bermuda by the Bermuda meteorological office on the previous day (*Macky*, 1951], not with the hurricane located some 500 mi southwest. These facts have been kept in mind in the present study in every case where microseisms were attributed to a distant source.

Donn [1954b] recognized at Palisades microseism storms of approximately the same 7–10-sec periods to be discussed here, which he could correlate with storms along the coast of Alaska and the Pacific Northwest. From a study of the three components of motion he showed that these microseisms arrive at Palisades as Rayleigh waves from the direction of the Pacific storms. Figure 1 shows a Palisades seismogram (pendulum period, 12 sec; galvanometer period, 15 sec) of microseisms from the Pacific coast. Also shown in Figure 2 are vertical and north components of the Palisades seismograms (pendulum period 12 sec, galvanometer period 15 sec) for the *Rg* phase from the Yukon aftershock at 14h 02m 25s on March 1, 1955. Comparison of the

* Contribution No. 216, Lamont Geological Observatory

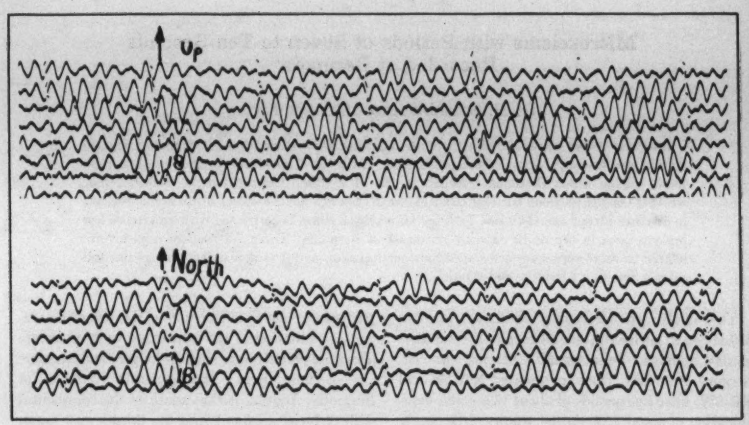

FIG. 1 – Palisades seismograms of microseisms 16h–18h, November 18, 1954

particle motion in the two cases shows that both are Rayleigh waves with approximately equal periods traveling in the same general direction, and it will be noted that the *Rg* phase is the largest in amplitude of any phase recorded on the earthquake seismogram and much larger than the microseisms. The direction of arrival at Palisades of microseisms from the storm and of the *Rg* phase is approximately NW, and the EW components confirm the conclusion stated about Rayleigh waves and orbital motion in both cases.

The *Rg* phase and the microseisms shown in Figures 1 and 2 offer good support for the suggestion recently made by several writers [*Ewing* and *Press*, 1952; *Båth*, 1953; *Gutenberg*, 1954, 1955] that the *Rg* phase represents propagation of the same type as that which is so efficient in transmitting microseisms of the same period along continental paths.

In previous studies of the continental earthquake phases *Lg* and *Rg* [*Press* and *Ewing*, 1952], it was found that although the phases *Rg* and *Lg* are propagated very efficiently across continents, they are greatly attenuated or completely eliminated if a short segment of the path lies in the ocean at either end of the propagation path. It has also been pointed out that very strong short-period surface waves are propagated along purely oceanic paths [*Ewing* and others, 1954]. The mode of propagation and even the type of waves is not entirely clear, but it is a fact that these waves also are either strongly attenuated or stopped completely at continental boundaries. For example, the large earthquake of July 9, 1953, 21h23m48*s* at 30°N, 42½°W, gave surface waves at Bermuda in the period range of 8–12 sec with trace amplitudes up to 15–20 mm on the Milne-Shaw seismographs, but Palisades recorded no surface waves at all in this period range. The epicentral distance to Palisades is about 28° compared to 19° for Bermuda, and the Palisades instruments are far more sensitive. No effect other than the strong attenuation at the continental boundary noted by *Oliver* and others [1955] seems capable of explaining this observation.

In the other direction, the attenuation on crossing the continental margin is clearly shown by data of *Press* and *Ewing* [1952] and *Oliver* and others [1955]. These data show that a 100-km segment of ocean crustal structure can prevent the occurrence of *Lg*. Many examples of this have been observed. For instance, the strong *Rg* phase shown on the Palisades seismogram in Figure 2 was not recorded at Bermuda. Bearing in mind this attenuation at the continental margin it seems unlikely that 7–10-sec microseisms can reach Bermuda from a source in the Pacific Northwest as discussed by *Carder* [1955ab].

The present study covers the period from September 1951 through December 1954. There were thirty-four definite 7–10-sec microseism storms recorded at Bermuda during this period. There were certainly other occasions when the 7–10-sec microseisms were recorded very weakly or obscured by shorter-period microseisms, but the list shown as Table 1 contains all examples of definite storms of

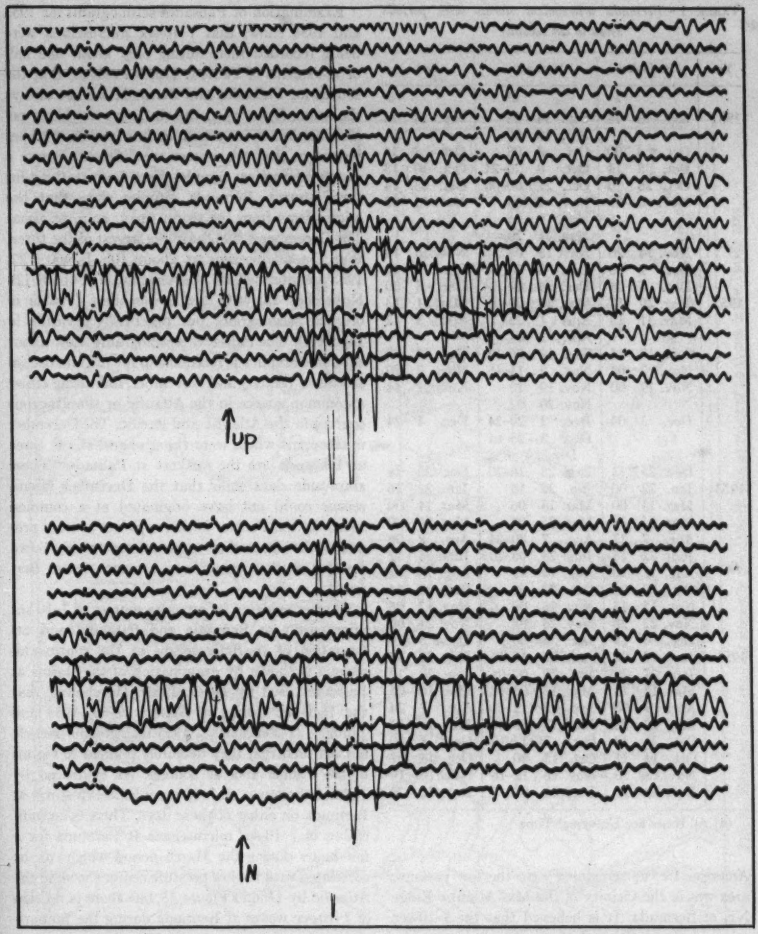

FIG. 2 – Palisades seismograms of the Yukon aftershock, March 1, 1955 at 14h 02m 25s

7–10-sec microseisms. (Universal time is used throughout.)

In some previous microseism studies perhaps not enough attention has been paid the fact that simultaneous storms along the North Pacific Coast and the North Atlantic Coast of North America are very common. Weather conditions along the Atlantic coast during the 34 7–10-sec storms were studied. In several cases, weather conditions along the Pacific Coast were also studied. It was found that, with one exception, in every case when Bermuda received the 7–10-sec microseisms, there was a low-pressure area or cold front in the near vicinity of the continental shelf along eastern North

TABLE 1 – *Bermuda microseism storms with periods seven to ten seconds*

Year	Beginning		Max. amp.		End	
		h[a]		h[a]		h[a]
1951	Sep. 12	14	Sep. 14	08	Sep. 18	14
			Sep. 15	00		
	Oct. 3	00	Oct. 3	08	Oct. 3	14
	Oct. 8	14	Oct. 8	20–24	Oct. 10	13
	Oct. 26	10	Oct. 27	00–06	Oct. 28	14
	Nov. 6	06	Nov. 7	03	Nov. 13	03
			Nov. 9	15		
			Nov. 11	20		
	Nov. 14	20	Nov. 15	08	Nov. 16	14
	Dec. 2	06	Dec. 3	03	Dec. 5	00
	Dec. 5	06	Dec. 6	00	Dec. 8	00
1952	Mar. 29	17	Mar. 30	00–06	Mar. 31	13
	Mar. 31	13	Apr. 1	22	Apr. 3	12
			Apr. 2	04		
	Sep. 10	14	Sep. 11	06–12	Sep. 12	10
	Nov. 2	03	Nov. 2	14–15	Nov. 2	20
	Nov. 19	00	Nov. 19	20	Nov. 21	14
			Nov. 20	02		
	Dec. 2	04	Dec. 2	20–24	Dec. 4	24
			Dec. 3	23 to		
			Dec. 4	05		
	Dec. 25	13	Dec. 25	18–20	Dec. 25	24
1953	Jan. 22	06	Jan. 22	10	Jan. 22	16
	Mar. 13	00	Mar. 13	06	Mar. 14	00
	Mar. 24	18	Mar. 25	08	Mar. 26	00
	Apr. 7	17	Apr. 7	20–24	Apr. 8	06
	June 22	15	June 23	08–20	June 26	12
	Aug. 17	20	Aug. 18	02	Aug. 18	12
	Oct. 20	00	Oct. 20	08	Oct. 20	14
	Nov. 15	15	Nov. 16	00	Nov. 17	06
	Nov. 22	20	Nov. 23	08	Nov. 24	00
	Dec. 4	14	Dec. 5	00	Dec. 5	14
1954	Jan. 19	00	Jan. 20	10–16	Jan. 22	14
	Jan. 27	20	Jan. 28	00–06	Jan. 28	12
	Mar. 14	13	Mar. 15	05–12	Mar. 16	05
	Apr. 7	00	Apr. 7	12	Apr. 7	24
	May 12	22	May 13	16–20	May 14	14
	Oct. 6	13	Oct. 7	12–18	Oct. 8	00
	Oct. 14	21	Oct. 15	00	Oct. 15	07
	Nov. 18	10	Nov. 18	12–16	Nov. 19	19
	Dec. 30	20	Dec. 31	05	Dec. 31	20

(a) All times are Universal Time.

America. In the remaining case the low pressure area was in the vicinity of the Mid-Atlantic Ridge NE of Bermuda. It is believed that the 7–10-sec microseisms at Bermuda from this storm may be due to ocean swell arriving at Bermuda from the storm. The weather maps also clearly show that in four of these cases, April 7, 1953, June 23, 1953, October 3, 1951 and November 15, 1951, there was no indication of storms in the Pacific Coast area (Fig. 3). Thus it is demonstrated that in four cases the long period microseisms at Bermuda are of Atlantic origin. It will be shown below that the same is true for all 34 cases.

Examination of Palisades seismograms for 1953 and 1954 shows that 7–10-sec microseisms were being recorded there during only about one half of the storms of Table 1. This is evidence that the source for Palisades and Bermuda are not always the same. Even when the stations record long period microseisms at the same time it can sometimes be shown that the sources are different. Figure 4 shows microseism samples from both stations for three storms. Bermuda samples show that the microseisms from the storm (max. amp. at about 23h December 3, 1952) are the largest of the three, that the microseisms at about 10h January 22, 1953 are intermediate, and that those at about 12h November 18, 1954 are the smallest (visible in original seismogram, but practically invisible in Figure 4). The Palisades seismograms show about the same amplitude relationship for the microseism storms of January and November, indicating either a common source in the Atlantic or simultaneous sources in the Atlantic and Pacific. The December microseisms which were the strongest of the three at Bermuda are the weakest at Palisades. These amplitude data show that the December microseisms could not have originated at a common source in the Pacific. Either separate sources produced the December microseisms at the two stations or they came from a source nearer Bermuda.

Further evidence for separate sources of 7–10-sec microseisms at Bermuda and Palisades and attenuation of the microseisms at the continental margin is shown by examination of the storms at Palisades used by *Donn* [1954]. He showed that the 7–10-sec storms of March 29–30, 1953 and January 31–February 1, 1953 had ground-particle motion such that they definitely pointed to storms in the Pacific area as sources. As evidenced by Table 1 there was no 7–10-sec microseism storm at Bermuda on either of these days. There is an indication of 7–10-sec microseisms at Bermuda for a few hours during the March period which can be correlated with the low pressure center shown in the Atlantic by Donn's Figure 15, but there is no sign of 7–10-sec waves at Bermuda during the January storm.

Carder [1955b] noted that microseism periods were different at Bermuda and continental stations for the case when he related the Bermuda microseisms to the Pacific storm of November 1–3, 1948; this also suggests different sources. He attributed the difference in period to some property of microseism propagation across the Atlantic Ocean, but for this same microseism storm he noted a rise in microseisms at Honolulu with periods the same as

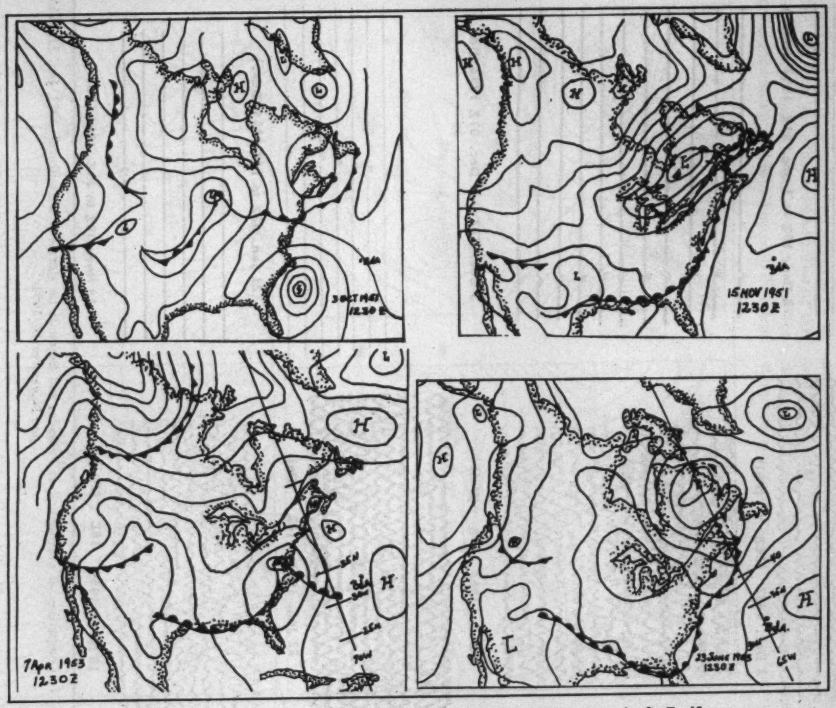

FIG. 3 – Weather maps showing storms in the Atlantic area at times of no storm in the Pacific area

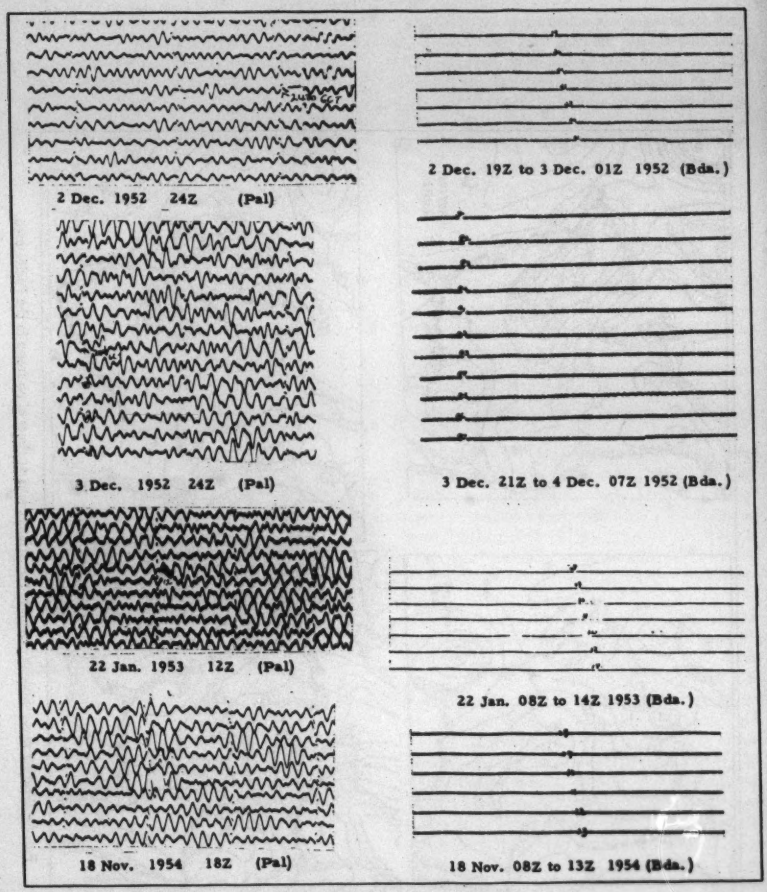
2 Dec. 1952 24Z (Pal)
2 Dec. 19Z to 3 Dec. 01Z 1952 (Bda.)
3 Dec. 1952 24Z (Pal)
3 Dec. 21Z to 4 Dec. 07Z 1952 (Bda.)
22 Jan. 1953 12Z (Pal)
22 Jan. 08Z to 14Z 1953 (Bda.)
18 Nov. 1954 18Z (Pal)
18 Nov. 08Z to 13Z 1954 (Bda.)

FIG. 4 – Comparison of microseisms at Palisades and Bermuda for storms of December 3, 1952, Jan. 22, 1953, and November 18, 1954

observed at Sitka. He did not definitely associate the microseisms at Honolulu with the storm near Sitka. Inspection of the weather maps makes it reasonable to believe that the 8.5-sec microseisms at Honolulu did originate in the storm near Sitka, but that the 10-sec microseisms at Bermuda originated in a cold front along the Atlantic coast of North America.

Comparison of the weather maps for 12, 13, 15 and 16 September 1951 (Fig. 5) and Table 1 shows that a storm in the North Atlantic may also be a source of 7–10-sec microseisms at Bermuda. On September 12 at 06h30m there is no storm in either the Atlantic or Pacific near the continental shelf of North America. There is an intense storm centered 40°N and 47½°W and another storm centered off the east coast of southern Greenland. The 7–10-sec microseisms are still appearing weakly at 06h30m on

September 13 and the significant changes in the weather map are: (1) the intense storm nearest Bermuda is centered 40°N 42°W; (2) the storm east of Greenland has moved about 300 mi eastward; (3) a small low-pressure area has moved off the continent and is centered about 53°N and 52°W with a cold front extending southwest. During this time Palisades recorded some very weak 7–10-sec microseisms which probably originated in the storm moving off the continent. During the hours the 7–10-sec microseism activity is at a maximum at Bermuda the Palisades level is very low and the predominant period is shorter than seven seconds as seen in Figure 6. During this time of maximum activity at Bermuda there was no storm in the coastal areas and the Greenland storm was moving northeast of Iceland. However, the nearby intense storm was still in the vicinity of the Mid-Atlantic

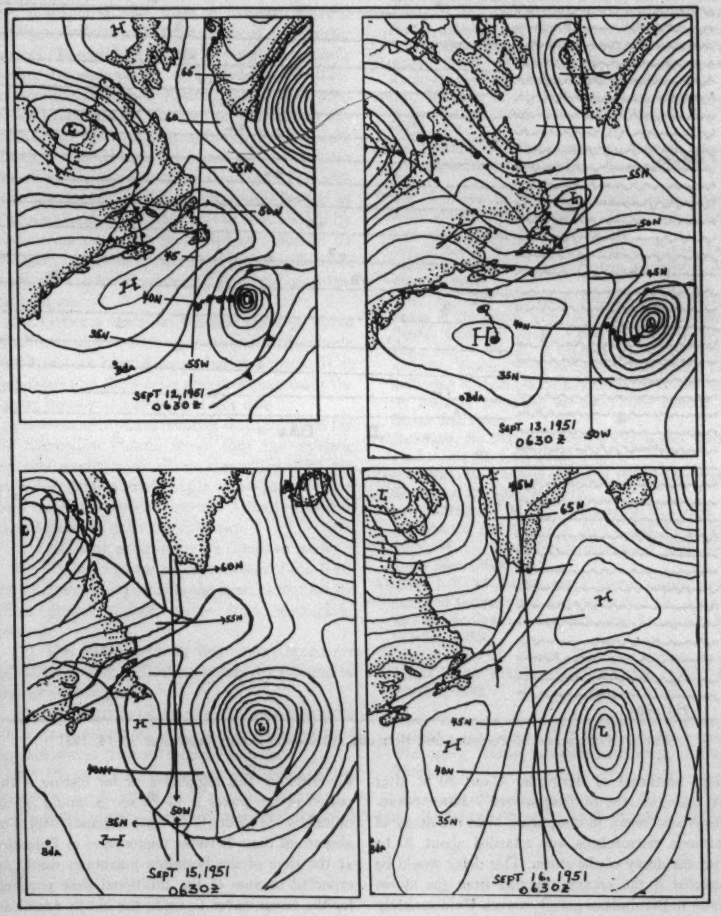

FIG. 5 – Weather maps showing storm in the Atlantic which generated 7–10-sec microseisms at Bermuda

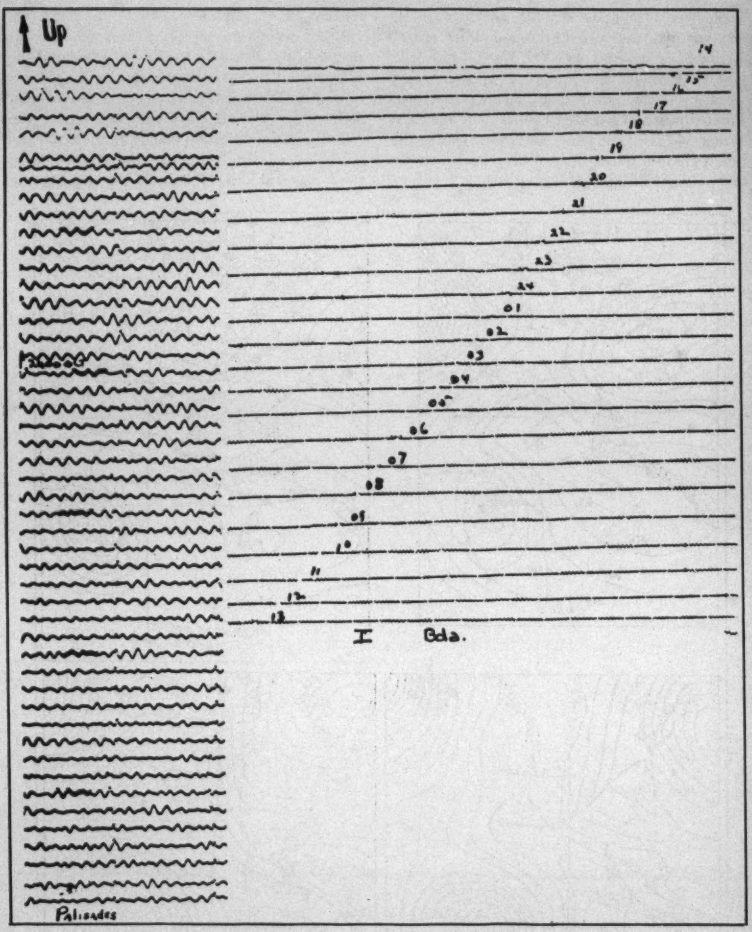

FIG. 6 – Comparison of Palisades and Bermuda microseisms during September 13–14, 1951

Ridge northeast of Bermuda. About 30 hr after this storm started to dissipate the 7–10-sec microseisms also began to disappear. Thus the decay of Bermuda microseisms was retarded about 30 hr after the decay of the storm. This delay would be expected if the energy traveled from the storm center to Bermuda as gravity waves. Unfortunately no records of ocean waves at Bermuda are available for checking this suggestion or for testing if the period of the waves is 14–20 sec as would be required by the theory of *Longuet-Higgins* [1950]. The absence of these 7–10-sec microseisms at Palisades at the time of the Bermuda maximum would be expected because of the additional time required for the ocean waves to reach the North American coast. The fact that they did not appear the follow-

ing day is taken to mean that the ocean waves never reached the continent with large amplitudes.

Donn and others [1954] reported that the period of microseisms generated by a cyclone south of Newfoundland on November 18–19, 1952 and recorded at Palisades was 6.5 to 8.5 sec, and suggested that the deep ocean area about 42°N and from 50° to 65°W might be the place of origin of these longer periods. It now seems likely that these microseisms are generated at the continental margin; propagating from there to Palisades along a continental path with attenuation of the shorter periods. Bermuda recorded 7–10-sec microseisms during this same period. At Palisades the 7–10-sec microseisms from these Atlantic storms have been called irregular with confused orbital motion different from those originating on the Pacific Coast [*Donn*, 1954]. Attenuation alone can account for the very smooth wave trains arriving at Palisades from the Pacific. The confused orbital motion at Palisades from Atlantic storms can be explained by considering the sector subtended at Palisades by the generating area [*Donn*, 1954] and the effects of scatter as the waves propagate along the continental margin.

Sometimes a storm on the east coast of North America makes 7–10-sec microseisms at Bermuda but Palisades records only shorter periods. It is suggested that the shorter periods simply mask the longer periods at Palisades in this case.

Close examination of weather maps for all of the 34 microseism storms shows that the Atlantic weather conditions in all cases were like those discussed in detail above, that is, a low pressure or a cold front was present near the Atlantic Coast of North America or in the Atlantic.

The following conclusions are therefore made:

(1) The mechanism of transmission of the 7–10-sec microseisms is probably the same as that for the short period surface waves from earthquake sources.

(2) The microseisms in this period range are propagated very well along purely continental or purely oceanic paths.

(3) The continental margin acts as a barrier to these microseisms as it does to the short-period surface waves from earthquake sources.

(4) These 7–10 microseisms are generated by storms and cold fronts along oceanic margins.

(5) These microseisms may be generated by the arrival at Bermuda of ocean swell from a storm in the Atlantic.

Acknowledgments—This investigation was supported by Contract N6 onr 271 24 between the Office of Naval Research and Columbia University.

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Two Grid Systems that Divide the Entire Surface of the Earth into Quadrilaterals of Equal Area

HARRY P. BAILEY

Abstract—Employed with unconventional spacings, meridians and parallels can block out quadrilaterals equal in area upon the surface of a sphere. Such a grid system can be transferred to any map projection and still retain the property of reference to a common unit area on a sphere, regardless of the apparent distortions of the grid in mapped form. Hence, conformal projections can be used with subjects for which areal comparisons and analyses are important. Two methods of laying out the grids are given, one employing respaced parallels, the other respaced meridians. Both result in patterns that can form quadrilaterals over a wide range of sizes, but the grid with respaced parallels is more accurate and legible.

Introduction—Grids composed of elements equal in area are useful for the statistical analysis of subjects too complex for examination as a whole. The surface of the Earth is certainly such a subject, but at the present time no system has been agreed upon for dividing its entire surface into elements equal in area. Thus, geophysical sciences have been lacking a tool taken for granted in many other disciplines.

Here it is proposed that such division of the Earth's surface be made by suitably selected meridians and parallels. A grid formed of meridians and parallels can create quadrilaterals alike in area, even though unlike in shape. Furthermore, grids of meridians and parallels have advantages in simple definition, ease of application to any map projection, and retention of their usual services in direction and location finding.

The desired patterns are called here 'area-reference' grids after the fact that chief emphasis rests upon the areas lying between grid lines, rather than upon the location and identity of the grid lines themselves. The conventional grid does not create quadrilaterals equal in area on a sphere, of course, because the meridians converge toward the poles. The consequent poleward decrease in the area of quadrilaterals has been worked out by *Woodward* [1929].

To change a grid from conventional to area-reference form either the parallels or the meridians can be respaced. If the parallels are respaced, the object is to create zones equal in area. Those zones, if combined with conventional lunes (which are also equal in area) will then create quadrilaterals of equal area. In the other case conventional zones are accepted; there it is necessary to widen the meridional interval according to the poleward decrease in area of the zones, in effect preventing convergence of the meridians. The two types of adjustment are shown in sectors B and C, Figure 1, where the conventional grid is also seen in sector A. Grid C forms quadrilaterals most nearly alike in shape, but the solution is neither precise nor elegant, as the areas of quadrilaterals cannot be made exactly equal from one zone to another, and north-south lines are not continuous. The grid in sector B, however, is both precise and continuous; its sole defect is pronounced latitudinal variation in shape (but not area) of its quadrilaterals.

Design of area-reference grids—On a sphere, the area between two parallels (a zone) is proportional to the vertical distance between the planes containing the parallels [*Sigley* and *Stratton*, 1942, pp. 100–101]. In terms of trigonometry, then, the area of a zone is proportional to the difference between the sines of its bounding parallels. From that relation both types of area-reference grids are determined. Other considerations relate only to control of the size and proportion (height to width) of quadrilaterals in the grid pattern. Appropriate steps for design of area-reference grids are as follows.

Relations useful in defining area-reference grids—The area of a hemisphere A is 98,470,000 mi², or 255,040,000 km² [*Woodward*, 1929].

The area of a single quadrilateral a is in the same units as A.

A For the determination of meridians and parallels of area-reference grids of the first type (grids with respaced parallels):

(1) The total number of quadrilaterals in a hemisphere Q is A/a. (Any great circle of course divides the globe into two hemispheres. Throughout this paper, however, hemisphere refers to one of the two divisions made by the equator.)

(2) The number of zones in a hemisphere Z suited to Q is taken from line A, Figure 2.

(3) The altitude h of each zone is $1/Z$.

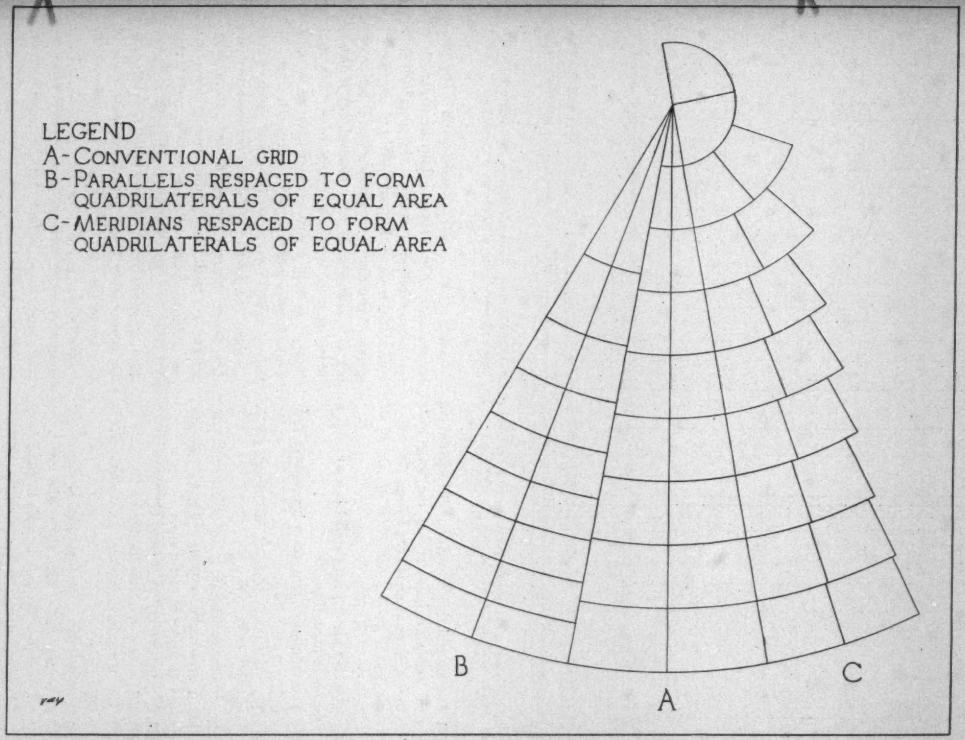

FIG. 1 – A comparison of the conventional grid with two methods of forming quadrilaterals of equal area; as a polar-equidistant projection has been employed, the quadrilaterals of equal area appear here to increase slightly in size from pole to equator, but on a sphere they show true uniformity in area with Grid B, and approximate uniformity with Grid C

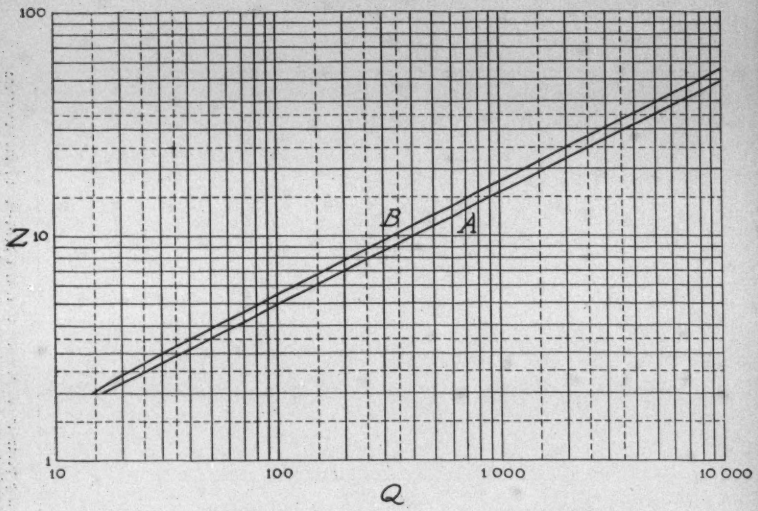

FIG. 2 – Relation of the number of zones in a hemisphere (Z) to the number of quadrilaterals in a hemisphere (Q) for area-reference grids of the first type (A) and area-reference grids of the second type (B)

(4) The natural sine of each parallel located on the poleward boundary of the zone with the same number, starting from the equator, is: $\sin P_1 = h$, $\sin P_2 = 2h$, $\sin P_3 = 3h, \cdots$

(5) The latitude of each parallel is read from a table of natural sines.

(6) The number of lunes in a hemisphere L is Q/Z.

(7) The meridional interval in degrees $\Delta\lambda$ is $360/L$.

B For the determination of meridians and parallels of area-reference grids of the second type (grids with respaced meridians):

(1) Q is determined as in step (1) above.

(2) Z is taken from line B, Figure 2.

(3) The latitudinal interval in degrees $\Delta\phi$ is $90/Z$.

(4) The latitude of each parallel in degrees is: $P_1 = \Delta\phi$, $P_2 = 2\Delta\phi$, $P_3 = 3\Delta\phi, \cdots$

(5) The number of quadrilaterals in each zone, where the zones number from the equator, is: $q_1 = Q \sin P_1$, $q_2 = Q(\sin P_2 - \sin P_1)$, $q_3 = Q(\sin P_3 - \sin P_2), \cdots$

(6) The meridional interval in each zone, in degrees, is: $\Delta\lambda_1 = 360/q_1$, $\Delta\lambda_2 = 360/q_2$, $\Delta\lambda_3 = 360/q_3, \cdots$

Control of the area of quadrilaterals—The procedures listed above assume that the design of an area-reference grid starts with the specification of a unit area a for each quadrilateral in the desired system. Following that specification, Q (the number of quadrilaterals in a hemisphere) is determined from the quotient of A/a. In practise, that quotient is only a goal of design, for Q actually results from a combination of lunes with zones. As that combination must be made from whole numbers, the product of LZ can only approximate A/a, hence the grid can supply only an approximation of a itself. For quadrilaterals smaller than one million square miles, a can be met within ± 0.5 pct of specification with area-reference grids of the first type [*Bailey*, 1956]. Discrepancies are considerably larger in area-reference grids of the second type as a result of limitations still to be discussed.

Another error, which affects both types of grids, arises from the fact that they have been designed for a spherical shape rather than a spheroidal figure more like that of the Earth. This error amounts to no more than one part in 250 at the worst, and so can be ignored for any purpose to which the grids are likely to be put. However, by considering all latitudes as 'authalic,' correc-

tion to geodetic latitudes on the Clarke spheroid can be made from tables prepared by *Adams* [1949], thus making the area of quadrilaterals true on that spheroid.

Control of the proportion of lunes to zones—The procedures listed above apply to a wide range in the numbers of quadrilaterals in the grid patterns, but regardless of their texture certain similarities are produced in the reticules. These similarities are seen in the proportion of lunes to zones, a proportion which should be controlled so that reasonable shapes are given to the quadrilaterals.

With area-reference grids of the first type based upon line A in Figure 2, all patterns show four times as many lunes as zones in a hemisphere. Line A was plotted from

$$Q = CZ^2 \tag{1}$$

where Q and Z are as before, but C stands for the ratio of lunes to zones in a hemisphere. A numerical value of 4 for C is appropriate to map projections centered along the equator. For polar projections, a lesser proportion of lunes is advisable. Any ratio between 2 and 5 might be useful, and changes in C do not affect the accuracy of the grid.

A similar statement cannot apply to area-reference grids of the second type. There, inequalities in the areas of zones are made good by adjustment of the meridional interval. As only whole numbers of quadrilaterals are permissible, fractional parts computed in step **B** 5 must be absorbed at the expense of accuracy. Discrepancies are worst in the polar cap, where the number of quadrilaterals is the least. As a preventive, grids taken from line B in Figure 2 always provide a polar cap divided nearly exactly into four parts, a relation achieved by

$$C_1 = q_n \sin \Delta\phi / Z(1 - \cos \Delta\phi) \tag{2}$$

where C_1 is the ratio of the number of quadrilaterals in the zone adjacent to the equator to the number of zones in a hemisphere, and q_n is the number of quadrilaterals in the polar cap. If q_n is 4, then C_1 can be taken as 5 for these purposes. Using that numerical value for C_1, line B in Figure 2 results from

$$Q = C_1 Z / \sin \Delta\phi \tag{3}$$

Hence, by using (3) as described, all grid patterns show not only 4 quadrilaterals in the polar cap, but also 5 times as many quadrilaterals in the zone adjacent to the equator as zones in a hemisphere. By that scheme, areas of quadrilaterals in any zone fall within ±3 pct of the mean for the hemisphere (A/Q).

Construction of area-reference grids—The area-reference grids designed here have been based upon the distribution of area upon the surface of a sphere. Any such design, once adopted, is absolute in the sense that the parallels and meridians need not be redefined when transferred to map projections. Regardless of appearance in mapped form, an area-reference grid always refers to units of equal area on the spherical Earth. It should also be understood that the presence of an area-reference grid does not change in any way the properties of a map projection as such.

In computing and plotting the grids it is advantageous to use decimal fractions of degrees. Natural sines to the thousandth of a degree can be read without interpolation from tables easily available [*Peters*, 1942]. Numbering the grid on the finished map also involves fractional parts of degrees; here again use of decimal degrees is advisable. The staggered meridians of the second type of area-reference grid cannot be readily numbered by any method on maps of small scale, or where the meridians are crowded. Intervals for area-reference grids of the first type for even areas from 25,000 to 1,000,000 sq mi and 50,000 to 2,500,000 sq km are given in *Bailey* [1956].

While either type of area-reference grid can be applied to any map projection, it is natural that area-reference grids of the first type be applied to cylindric projections, and those of the second type to polar projections. The latter case requires subdivision of circles into n parts (step **B** 5). This troublesome procedure can be simplified by laying off with dividers the sides of an inscribed polygon, where the length l of a side is

$$l = 2r \sin 180/n \tag{4}$$

where r is the radius of the circle in the same units as l.

Applications of area-reference grids—A proposal for use of these grids has not been made previously in the field of geophysics, to the best of my knowledge, and so their applications are mainly of future determination. Types of carto-statistical problems for which they appear suited are

(1) integration of continuous distributions of subjects representing depth or intensity, such as precipitation or insolation; (2) mensuration of comparative areas of discrete objects rendered by mapped outlines of their limits, such as the areas

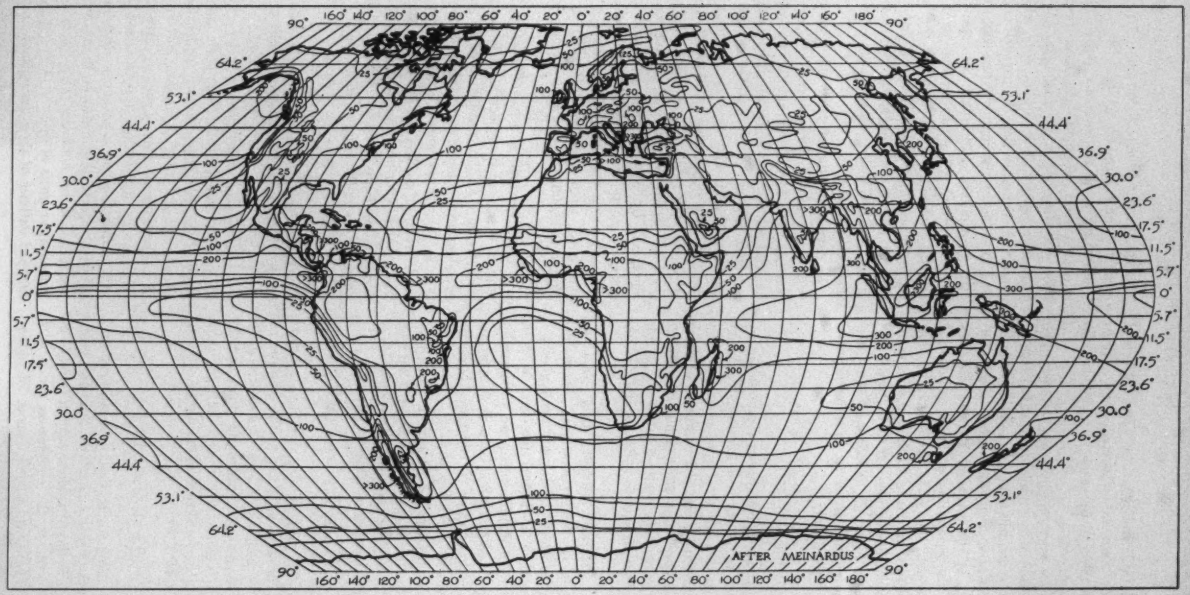

FIG. 3 – Average annual precipitation (cm), shown on an equal-area projection (Eckert's no. 6) with an area-reference grid of the first type (a = 274,000 mi²)

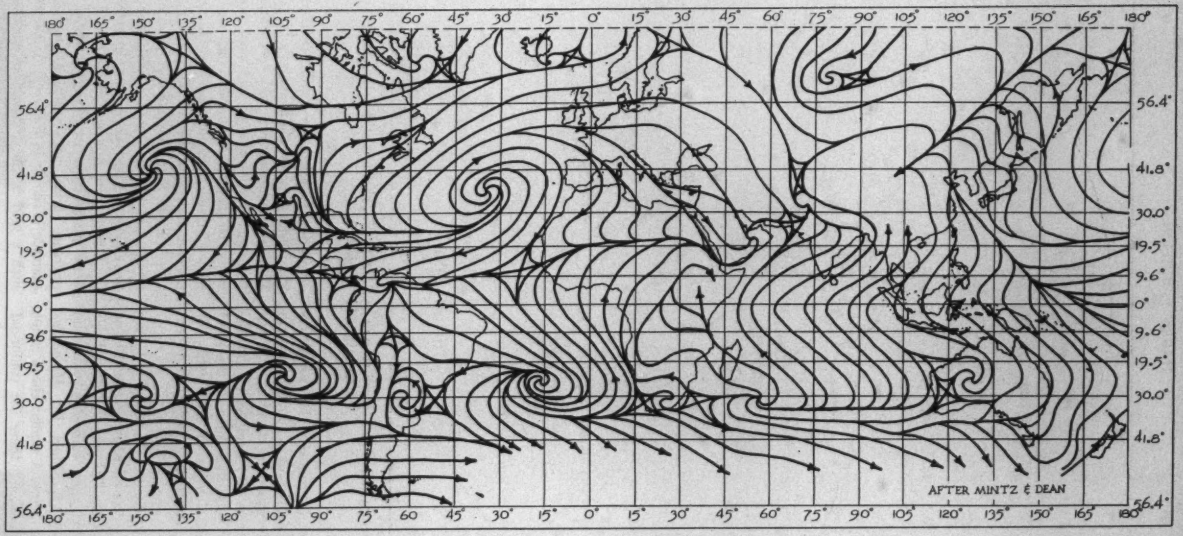

FIG. 4 – Direction of the mean surface wind in July, shown on the cylindrical conformal (Mercator) projection, with an area-reference grid of the first type (a = 684,000 mi²); note that whole quadrilaterals carry only to latitude 56.4°; the polar tier cannot be shown completely

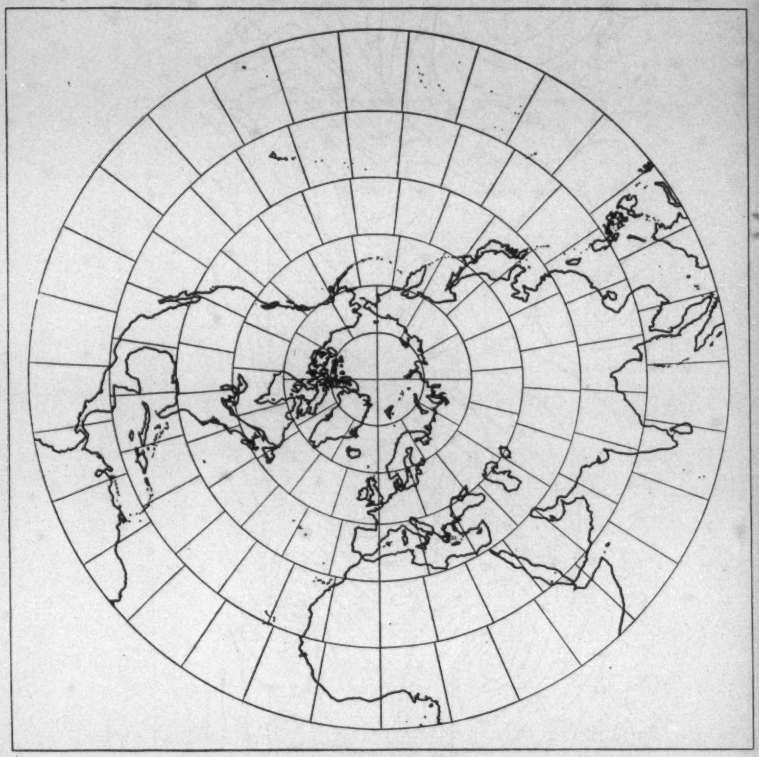

FIG. 5 – An area-reference grid of the second type (a = 820,600 mi^2), shown on the polar azimuthal conformal (stereographic) projection

of climatic regions; (3) dot-counting for determining the spatial density of a population, as in the analysis of the distributions of station-networks, or observations; (4) analysis of the distribution of vector quantities, such as the wind field; and (5) determination of areal units for sampling purposes, where equal weight is desired for each unit.

The first type of problem is illustrated in Figure 3, where annual isohyets allow precipitation to be estimated in each of the 720 grid elements. Their mean, 99.7 cm, compares favorably with the figure of 100.2 cm furnished by *Meinardus* [1934 ab] from planimetry. A similar check is not possible with Figure 4, for there the conformal projection required for correct rendition of the wind field does not allow analysis by planimeter. With the area-reference grid, however, the comparative extent of cyclonic and anticyclonic fields is readily determined on the Mercator projection without the necessity of subsequent transfer to an equivalent projection.

It is likely that area-reference grids of the first type, as in Figures 3 and 4, will be more useful than those of the second type. In satisfaction of the fifth type of problem cited, that of sampling, some justification may exist for use of area-reference grids with respaced meridians. An example is shown in Figure 5. A possible use for such a grid is the collation of marine weather

observations, where a uniform latitudinal span might be considered an attribute of the sampling pattern.

As a climatologist, applications of area-reference grids occur to me most readily in that field. However, uses other than the meteorological examples given here will doubtless occur to persons in the several fields of geophysics.

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Discussion of "Development and Significance of Seepage Steps in Slope Erosion"

BY R. F. HADLEY AND B. N. ROLFE

[*Trans.*, **36**, 792–804, 1955]

Don U. Deere and Dipankar Niyogi (Departments of Civil Engineering and Geology, University of Illinois, Urbana, Illinois; Department of Geology, Indian Institute of Technology, Kharagpur, India.)—The authors have presented an interesting description of the occurrence and development of seepage steps in the semi-arid Great Plains. Subsurface flow at the contact between the more permeable surficial mantle material and the underlying more impermeable weathered bedrock is shown to be responsible for the formation of these features. It appears that an additional requisite for the development of seepage steps is a mantle material which is sufficiently cohesionless, or which becomes essentially cohesionless upon saturation by rainfall, and in which the grains are sufficiently small (fine sand or silt size) to be eroded at an exposed face by the seepage flow emerging at the contact of the permeable and more impermeable zones. The grain-size analyses show that the mantle material of the area studied meets these requirements, with approximately 75 pct of the soil constituents being of silt and fine sand size and from 20 to 25 pct only of clay size (equivalent diameter less than 0.002 mm).

The mechanism of failure which results in the development of the seepage steps may be considered to consist of two processes: subsurface erosion of the mantle at the contact between the mantle and the eroded bedrock, and shear failure or slumping of the mantle as the base is removed by the subsurface erosion. The seepage water would have its maximum velocity at the base of the mantle where the hydrostatic head is greatest. Consequently, the subsurface erosion would be concentrated along the contact plane of the mantle with the weathered bedrock. The erosion would consist of a grain-by-grain removal of the bottom part of the mantle material with the erosion progressing backward under the mantle until shear failure of the overlying mantle material takes place as the base support is removed.

The two processes of subsurface erosion and subsequent shear failure or slumping can probably be initiated only after rainfall, not only because the source of the seepage water is from rainfall but because saturation or wetting of the mantle is necessary to reduce the strength of the clay and silt binder. Loss in strength of the binder results in an overall loss in strength of the mantle material and also makes it more susceptible to subsurface erosion.

There is some doubt in the discussers' minds as to the location of the samples at Points 2 and 4. They are described as representing the bases of a single seepage step and a multiple seepage step, respectively. Consequently, according to the authors' earlier definition of base they should represent the weathered bedrock. However, in the discussion of the cumulative size distribution curves and the winnowing effect by transportation it appears that these samples were from the debris slopes. It would be helpful if the authors would comment on this in their closure.

R. F. Hadley and B. N. Rolfe (U. S. Geological Survey, Denver Federal Center, Denver, Colorado; Authors' closure)—Deere and Niyogi have written a constructive criticism of the article on seepage steps and the authors acknowledge their helpful discussion. We should prefer, however, that the term 'subsurface erosion' be avoided in a discussion of the genesis of seepage steps. This term implies a process similar to 'piping' with subsequent development of sinks or depressions on the seepage step slope. We feel that subsurface flow is the key to soil failure, thereby producing a surface material that is amenable to removal by overland flow.

With regard to the discussers' question about sample Points 2 and 4, the authors agree that these bases of a single and multiple seepage step respectively should be weathered bedrock by rigorous definition. However, the authors were derelict in not pointing out that the multiple step is usually covered with a veneer of debris material. Therefore, a profile at the base of a multiple step is a composite of debris material over weathered bedrock.

Discussion of "Free-Surface Flow Toward Partially Penetrating Wells"

BY MLADEN BORELI

[*Trans.*, **36**, 664–672, 1955]

Joel B. Cox (Alexander & Baldwin, Ltd., Honolulu, Hawaii)—The valuable and important contribution of Boreli adds greatly to our knowledge of this problem. His formula (17) has the great advantage of simplicity and ease of application, particularly if it is put in the form

$$\frac{Q}{k} = \alpha\left(1 + \frac{r}{H}\beta\right)(H_e^2 - t^2) \text{ for } R = 112r \quad (25)$$

$$\alpha = 0.66657\left[1 + 0.3\sin\left(1.8\,\frac{s}{H}\right)\right]$$

$$\beta = \frac{10\sin\left(1.8\,\frac{s}{H}\right)}{1 + 0.3\sin\frac{s}{H}}$$

Table 2 gives α and β for such computations, and they are also shown in Figure 4.

A critical review of present knowledge of this problem should certainly include consideration of the extremely important analysis by *Muskat* (1946, p. 274). The Muskat formula

$$\frac{Q}{k} = \frac{2\pi HD}{\frac{1}{2h}\left(2\ln\frac{4H}{r} - M(h) - \ln\frac{4H}{R}\right)} \quad (26)$$

$$M(h) = \ln\frac{\Gamma(0.875h)\Gamma(0.125h)}{\Gamma(1 - 0.875h)\Gamma(1 - 0.125h)} \quad (26a)$$

$$h = \frac{t}{H}$$

is derived by an important analysis for the case of $t = H_e$ or an artesian condition, and for wells closed at the bottom. To compare with gravity flow wells with open bottoms, empirical adjustments are needed. To fit the data presented by Boreli, these are to write the equation as

$$\frac{Q}{k} = \frac{\pi[H^2 - (s + t)^2]}{\frac{1}{2h}\left(2\ln\frac{4H}{r} - M(h) - \ln\frac{4H}{R}\right)} \quad (27)$$

for closed bottom wells where

$$\frac{R}{H} = 2$$

and

$$h = \frac{H_e}{H} - 0.19^3\sqrt{\frac{H_e}{H} - \frac{t}{s + t}} \quad (28)$$

For open-bottom wells this value of Q/k is to be increased approximately by the ratio of the area of bottom to the area of sides of the well up to the line of seepage. If this last distance is t'

$$\frac{Q}{k} = \left(1 + \frac{r}{2t'}\right)\frac{Q'}{k}$$

where Q'/k is for closed-bottom wells.

The Muskat equations appear to give satisfactory agreement with the results of relaxation and other analysis for all values of S/H less than $\frac{3}{4}$. A tabulation of $M(h)$ appears as Table 3.

A comparison of the various formulas considered is made in Figures 5, 6, and 7 for the case of $t = H - S$ or flow in an artesian stratum of constant thickness H. These diagrams point to a defect in the formula of Kozeny and that proposed by Boreli for low values of S/H. Any increase in flow with partial penetration of the well must be due to the effect of bottom flow and these formulas appear

TABLE 2 – *Values of the factors α and β for rapid solution of Boreli's formula by Eq. (25)*

$\frac{s}{H}$	α	β
0.00	0.6666	0.000
0.05	0.6845	0.875
0.10	0.7024	1.699
0.15	0.7199	2.469
0.20	0.7370	3.186
0.25	0.7536	3.848
0.30	0.7694	4.454
0.35	0.7844	5.007
0.40	0.7984	5.505
0.45	0.8114	5.951
0.50	0.8232	6.343
0.55	0.8338	6.684
0.60	0.8429	6.974
0.65	0.8507	7.215
0.70	0.8570	7.406
0.75	0.8617	7.548
0.80	0.8653	7.654
0.85	0.8664	7.693
0.90	0.8665	7.693

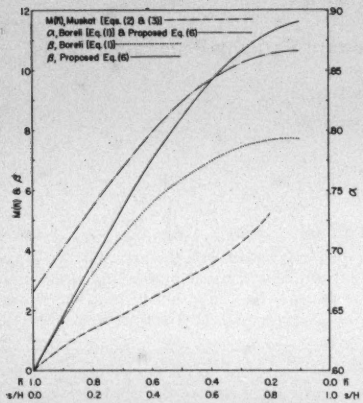

FIG. 4 – Values of factors used in Boreli Eq. (25), Muskat Eq. (2) and (3) and proposed Eq. (30)

to give too great an effect to well diameter with S/H between 0.5 and 1.0. In view of the relative simplicity of the Boreli formula and its advantages for high values of s/H it appears to be worthwhile finding a modification of the formula which will decrease the errors occurring with high values of r/H and high values of $t/(H - s)$. While the whole problem of the relationship of yield to well diameter needs further investigation, it would appear that the ratio of r/t is important as well as r/H. A purely empirical suggested form for this relationship which fits the Boreli data even more closely than his formula (17) is proposed

$$\frac{Q}{k} = \frac{\pi}{\ln \frac{R}{r}} (H_e^2 - t^2) \left\{ 1 + \left[0.30 + 7.767 \left(\frac{r}{H+t} \right) \cdot \left(1 + \sqrt{\frac{s}{H}} \right) \sin \left(1.8 \frac{s}{H} \right) \right] \right\} \quad (29)$$

at $R = 112r$

This again may be written

$$\frac{Q}{k} = \alpha \left[1 + \left(\frac{r}{H+t} \right) \beta \right] (H_e^2 - t^2) \quad (30)$$

$$\alpha = 0.6658 \left[1 + 0.3 \sin \left(1.8 \frac{s}{H} \right) \right]$$

$$\beta = \frac{7.767 \left(1 + \sqrt{\frac{s}{H}} \right) \sin \left(1.8 \frac{s}{H} \right)}{1 + 0.3 \sin \left(1.8 \frac{s}{H} \right)}$$

TABLE 3 – *Values of $M(h)$ (Eq. 26a)*

h	$M(h)$
0.20	5.1966
0.21	5.0868
0.22	4.9814
0.23	4.8801
0.24	4.7825
0.25	4.6883
0.26	4.5972
0.27	4.5090
0.28	4.4235
0.29	4.3404
0.30	4.2595
0.31	4.1808
0.32	4.1040
0.33	4.0291
0.34	3.9559
0.35	3.8843
0.36	3.8142
0.37	3.7454
0.38	3.6782
0.39	3.6119
0.40	3.5469
0.41	3.4830
0.42	3.4202
0.43	3.3582
0.44	3.2972
0.45	3.2370
0.46	3.1776
0.47	3.1190
0.48	3.0610
0.49	3.0038
0.50	2.9471
0.51	2.8909
0.52	2.8353
0.53	2.7802
0.54	2.7256
0.55	2.6713
0.56	2.6174
0.57	2.5639
0.58	2.5107
0.59	2.4578
0.60	2.4051
0.61	2.3526
0.62	2.3003
0.63	2.2482
0.64	2.1961
0.65	2.1442
0.66	2.0923
0.67	2.0404
0.68	1.9885
0.69	1.9366
0.70	1.8845
0.71	1.8324
0.72	1.7801
0.73	1.7276
0.74	1.6749
0.75	1.6219
0.76	1.5687
0.77	1.5150
0.78	1.4609
0.79	1.4064

TABLE 3—(*Continued*)

$\frac{t}{t}$	$M\frac{t}{t}$
0.80	1.3514
0.81	1.2958
0.82	1.2396
0.83	1.1828
0.84	1.1250
0.85	1.0665
0.86	1.0071
0.87	0.9467
0.88	0.8851
0.89	0.8223
0.90	0.7582
0.91	0.6925
0.92	0.6253
0.93	0.5562
0.94	0.4850
0.95	0.4117
0.96	0.3358
0.97	0.2571
0.98	0.1752
0.99	0.0897
1.00	0.0000

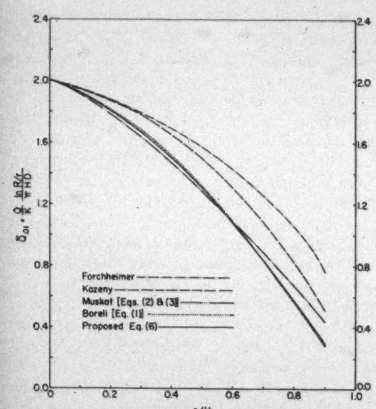

FIG. 5 – The flow to open-bottom wells in artesian strata by various formulas—with $r/H = 0.01$

The constants in this equation are chosen to fit Boreli's cases 1 to 7 and the comparison with the data of flow by relaxation methods is as shown in Table 4, which also shows the results obtained by the Muskat formula. Values of α and β for quick computation by (30) are given in Table 6. Eq. (29) gives results very close to the Muskat formula for small values of r/H but for $r/H = 0.05$, $s/H = 0.4$ and $t/(H - s) = 1$ the difference is about five per cent. This discrepancy needs further investigation as it is not altogether certain what the true value is with large diameter wells.

In conclusion it appears to the writer that the most accurate computations of the relationship between yield and drawdown with s/H less than 0.6 will usually result from the use of the Muskat formulas. For values of s/H greater than 0.6 closer

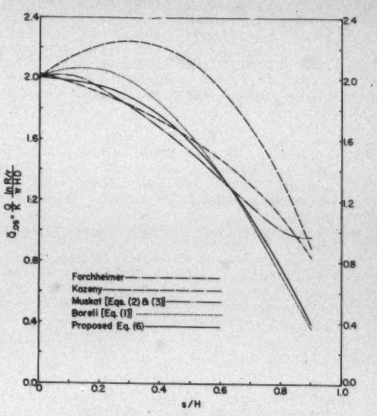

FIG. 6 – The flow to open-bottom wells in artesian strata by various formulas—with $r/H = 0.05$

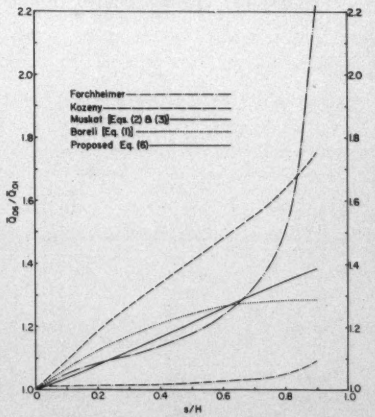

FIG. 7 – $\overline{Q}.05/\overline{Q}.01$ for flow to open-bottom wells in artesian strata by various formulas showing the estimated effect of well diameter

TABLE 4 – *A Comparison of Boreli's formula (25), Muskat formula (3) and proposed formula (30) for the seven cases analyzed by Boreli*

Case	$\frac{t}{H}$	$\frac{s}{H}$	$\frac{r}{H}$	$\frac{Q}{K \pi H^2}$ by relaxation	Δ_M	Δ_B	Δ_C
					pct	pct	pct
1	0.0000	0.2650	0.02208	0.14510	−0.3	−1.4	−1.0
2	0.1730	0.2594	0.02162	0.13439	−0.3	−0.7	−0.8
3	0.3490	0.2618	0.02182	0.11145	−0.8	−1.2	−1.6
4	0.1733	0.2600	0.01083	0.12960	−1.6	−0.2	−0.2
5	0.1713	0.2570	0.04283	0.14677	−2.8	0.0	0.0
6	0.1935	0.5206	0.02160	0.05886	−0.6	−2.5	−0.6
7	0.1739	0.0217	0.02174	0.19972	−0.6	−0.4	−0.1
8	0.1739	0.0000	0.02174	0.20548	0.0	0.0	0.0
Sum of $(\Delta)^2$					11.94	10.34	4.61

$\Delta_M = Q$ determined by muskat Method (modified as shown in Table 5 for open-bottom wells and with water surface extended to $R = 2H$) less Q obtained by relaxation analysis.

$\Delta_B = Q$ determined by Boreli less Q obtained by relaxation analysis.

$\Delta_C = Q$ determined By Equation (30) less Q obtained by relaxation analysis

While the sum of $(\Delta)^2$ is shown as a measure of goodness of fit, it does not imply that equally good results will obtain for other cases.

TABLE 5 – *The extension of the water table to $R/H = 2$ by Boreli's Equations (18) and (19)*

Case	H^a	$\frac{s}{H}$	$\frac{t}{H}$	$\frac{r}{H}$	$\frac{Q}{K \pi H^2}$
1	0.9834	0.2695	0.0000	0.02245	0.1519
2	0.9862	0.2630	0.1754	0.02192	0.1392
3	0.9881	0.2649	0.3532	0.02208	0.1103
4	1.0200	0.2548	0.1698	0.01061	0.1187
5	0.9320	0.2758	0.1838	0.04531	0.1681
6	0.9942	0.5236	0.1946	0.02773	0.05959
7	0.9781	0.0222	0.1774	0.02223	0.2084

[a]For $R = 112$ r

TABLE 6 – *Values of the factors α and β for rapid solution of Eq. (30)*

$\frac{s}{H}$	α	β
0.00	0.6658	0.000
0.05	0.6838	0.832
0.10	0.7016	1.737
0.15	0.7191	2.662
0.20	0.7362	3.581
0.25	0.7527	4.483
0.30	0.7685	5.355
0.35	0.7835	6.189
0.40	0.7975	6.980
0.45	0.8105	7.721
0.50	0.8223	8.410
0.55	0.8328	9.041
0.60	0.8420	9.613
0.65	0.8497	10.121
0.70	0.8560	10.565
0.75	0.8604	10.939
0.80	0.8643	11.262
0.85	0.8654	11.476
0.90	0.8655	11.643

results will be obtained by the Boreli formula. However, the ease of computation indicates a general usefulness for (29) which covers the range from $s/H = 0$ to 0.9 with errors probably less than five per cent with well diameter no more than 0.05 H; and it is especially easy to use by means of Table 6 and Figure 4.

Further investigation, either by relaxation methods or by experimental results using the analogy between electric current, resistance and potential (which should be relatively rapid and convenient for $t/(H - s) = 1$) should be made in the zone $s/H > 0.9$, and to determine with greater certainty the relationship between flow and r/H and r/t, particularly in the zone about $s/H = 0.4$ where the uncertainty appears greatest.

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MUSKAT, M., The flow of homogeneous fluids through porous media, J. W. Edwards, Inc., Ann Arbor, Michigan, 763 pp., 1946.

Mladen Boreli (Hydrotechnic Institute, Serbian Academy of Sciences, Belgrade, Yugoslavia; Author's closure)—The interesting and comprehensive discussion by Cox is a valuable contribution to the problem of partially penetrating wells. In particular, it points out that even in the problem investigated the results for artesian conditions of flow are applicable to free-surface flow. Actually, the discharges obtained for the cases of gravity flow investigated by relaxation differ very little from the discharges obtained by the Muskat formula for artesian flow (see Table 4 of discussion).

Cox, in analyzing the accuracy of different discharge formulas for partially penetrating wells, compares them to the basic Muskat formula. Applying the latter to comparatively large diameters, $r/H = 0.05$, Cox concludes that the Kozeny formula as well as (17) is defective in the region of small values of s/H. This conclusion seems to be debatable, because for larger values of r/H the Muskat formula becomes uncertain. As mentioned in the discussion, the Muskat formula assumes that the bottom is closed. But we have to remember that the formula is, furthermore, based on the assumption that the flux density over the well is uniform, the potential along the boundaries being an 'effective average' which turns out to be that at three-fourths of the distance from the top of the sand to the bottom of the well [*Muskat*, 1946, p. 273]. The latter assumption is proved by Muskat only for comparatively small diameters of well; $r/H = 0.0033$ and $r/H = 0.002$, that is, 15 to 25 times smaller than 0.05. There is no wonder, therefore, that the Muskat formula shows the biggest

disagreement for the biggest well ($r/H = 0.0428$). The writer's opinion is that Cox's conclusion about the inapplicability of (17) in the zone of small s/H is incorrect.

Using the data from the relaxation method, Cox proposes a new formula of more complicated structure. Although the application of the proposed formula is made less difficult by tables given in the discussion, the fact remains that the simplicity of a formula which can be used without the aid of any diagrams or tables is a most desirable and welcome advantage, even when a difference of one or two per cent may occur compared to the actual values.

For $r/H = 0.05$, $s/H = 0.4$, and $t/(H - s) = 1$, Cox obtains a difference of five per cent when comparing the Muskat formula to his own, and he comes to the conclusion that there is a necessity for further specific investigations in that zone. The writer's opinion is that in further investigations in the field of free-surface flow toward partially penetrating wells emphasis should be laid first of all on the region of large values of s/H. If greater accuracy is desired, the writer's investigations should be completed not only for $s/H > 0.9$, but also for $s/H > 0.8$, and even for $s/H = 0.7$; that is, for a zone where the analogy with the artesian flow becomes useless and where no data have been obtained by either the relaxation method or the electrical analogy. For the latter method there is need for special care and precaution, because under usual conditions the error can be two per cent or more.

The Muskat formula gives very useful data regarding the discharge. It is obvious, however, that the formula can be of no use regarding the free surface, and the writer's opinion is that his own free-surface equations are his principal contribution to the analysis of free-surface flow toward partially penetrating wells.

Discussion of "On the Offshore Circulation and a Convergence Mechanism in the Red Tide Region off the West Coast of Florida"

BY FRANK CHEW

[*Trans.*, **36**, 963–974, 1955]

Palle G. Hansen (Department of Oceanography, Texas A. and M. College, College Station, Texas)—Chew has drawn the isohalines for 0, 20, 50, and 150 m based on one cruise. The total area from the Florida Keys to the Mississippi Delta is covered by 25 stations, and a large number of these are well beyond the 100-fm line. This seems a rather meager basis upon which to draw the presented current maps. There is however, other information available, which substantiates the eddy named the Florida west coast cyclonic eddy in Chew's work.

Chew has inferred the existence of the Florida west coast eddy from the way the isohalines bulge in Figure 2 (compare Fig. 9). There are several ways to deduce currents from the isohalines. The current will be parallel to the isohalines if no mixing takes place, and if the isohaline pattern is stationary.

The current will cross lines of equal salinity in a stationary isohaline pattern, if mixing takes place. Chew interpreted the 'bulging' of the isohalines to mean that current was flowing in the direction of the bulging. But this means that mixing takes place, invalidating the statement (p. 968): "That is, over the shallow continental shelf, the water columns appear to move as a unit." This statement is used in the later mathematical exposition of the convergence mechanism.

That the salinity patterns are essentially the same at all depths does not imply that a vertical column moves as a unit, as assumed, but merely that the average current is in the same direction at all depths.

The basic equation for Chew's convergence mechanism is his

$$hA = (hA)_0 \tag{1a}$$

This equation expresses that the concentration of floating material is determined by the initial depth and the final depth, but is independent of how fast or in what way this depth change has come about as long as diffusion can be neglected.

The distance from where the loop current leaves the shore, to where it encounters the Florida Keys, can be judged to be about 250 naut mi from Figure 9. If the surface current is estimated at 5 mi/day, it will take 50 days for the Red Tide material to come back to land. It does not seem very likely that this mechanism can account for the patches of dead fish. Any smaller more localized eddies will not be able to bring about the concentration

necessary, because the ratio between final and initial depth will not be great enough.

The hypothetical eddy outside the Florida coast may of course still explain the northward motion of the fish mortality, but the 'bands' of fish must have some other explanation, such as tidelines or wind-rows.

In reference to horizontal convergence (p. 970), it must be emphasized that the horizontal convergence rate will be increased by a local depression but that it will likewise be decreased by a small elevation, and that the total concentration brought about must still be determined from (1a). The average concentration rate must therefore be the same for both examples on page 969 and page 970.

The theory of the dynamics of the offshore circulation, as set forth on page 971, assumes that the driving force is derived from the swift southbound branch of the loop current. But this again means that mixing is taking place in contradiction to the assumptions for the convergence mechanism (p. 968–969).

Eq. (15) does not taken into account the exchange of vorticity by horizontal mixing, but this exchange plays an important part in the change of relative vorticity as assumed by Chew in his next paragraph.

A second factor is mentioned on page 972 to explain why patches do not thin out again when the column is moving toward shore. It is assumed that the column can take such a path over the bottom that no significant divergence is experienced until it is some 10 to 20 mi offshore. But this is not possible since (1a) has to be satisfied.

The only reference to tidal effects is on page 973: "the possible effects of astronomical tides have not been analyzed but are here assumed negligible." The tidal currents in this part of the Gulf can actually be of the same order of magnitude as the currents considered in Chew's paper, and it seems unjustified to neglect them completely.

Frank Chew (The Marine Laboratory, University of Miami, Coral Gables, Florida; Author's closure)—Hansen has emphasized some of the fundamental difficulties generally encountered in oceanography: scarcity of data and the complexity of the actual condition. The Marine Laboratory has since occupied numerous hydrographic stations in the region of interest, and the preliminary picture emerging from these studies tends to support the earlier conclusions.

In a complex situation such as in the Red Tide region, it is desirable to single out of the many interplaying factors, the significant ones having greater bearing on the problem at hand. Mixing is always present, but I do not believe that in this instance its magnitude in the critical area is sufficiently large to negate the argument. The salinity patterns do not necessarily imply that water moves in a vertical column, but surely may so imply. In the absence of significant diffusion, a convergence mechanism is still probable even for the case when water is moving at different speeds but in the same direction at all depths. Hansen appears to have confused the magnitude with the rate at which the final horizontal cross-section of the column is achieved. The time rate is dependent on how fast or in what way this depth change has come about.

There is some vagueness in the text as to what are concentrated in a converging column. What are concentrated may well be biological environments favorable to *G. brevis* blooms. When blooms do occur, these environments become death traps to many marine animals entering from outside areas, which on death decompose to enrich the water with nutrients. As long as the death traps are conserved, there will be fresh killings of marine animals.

The bottom of the region of interest is not strictly uniform. No doubt there are minor troughs in the bottom oriented at an angle with the coast and extending from deeper water to near the coast. A shoreward-going column moving along a trough would have less tendency to diverge than a neighboring column outside the trough until it reaches the coastal end of the trough where significant divergence will occur.

The tidal currents are oscillatory and, though their magnitudes are relatively large near shore, their tidal excursions are small: about one mile in deeper water and three miles nearer shore. A limited study of the tidal effects is made in an unpublished study by the author and is available in the form of a technical report under the title: The Summer Circulation of the Florida West Coast Offshore Water as Deduced from the Pattern of Thermocline Depths and a Non-Geostrophic Equation of Motion.

Letters to the Editor

The European Daylight Meteor of November 17, 1955, and Its Remarkable Train

Among the outstanding meteors of our time, the fireball of November 17, 1955, merits a very high rank. This object appeared at $17^h\ 30^m$, Middle European Mean Time (or $16^h\ 30^m$ UT), shortly after sunset in this locality. Its track extended from western Switzerland to north-central France. Its range of visibility was extraordinary, encompassing Switzerland, Italy, southwestern and western Germany, Belgium, the Netherlands, England, and the shipping lanes funneling into the English Channel. Its motion was relatively slow; most observers give the duration of flight as a large number of seconds, approaching a minute, while others speak of two or more minutes, and one account has it three or four minutes. As seen from this station in the northern part of the Black Forest, the fireball was almost equal in apparent diameter to the full moon. Yellowish at first, it became bright green as it moved along, the brightness being much greater than that of the moon and even surpassing the albedo of Venus.

The meteor left a remarkable trail of fume, smoke, and gas, which reflected sunlight more brightly than does high cirrus. This trail or train showed a peculiar, vivid, light-blue glow as well, resembling the phosphorescent emission of modern neon lighting tubes. The column gradually became more and more tortuous and emitted more 'phosphorescence' which concentrated in different segments, so that the train gave the impression of developing knotty thickenings within itself, with the place of strongest glow sometimes slowly changing in such a way that a kind of pulsation traversed the column from bottom to top. The train was displayed some degrees above the horizon, with which it made a slight angle. The pulsations continued until deformation had so far progressed that the small cloud at the terminus or putative explosion point became detached and began moving away ($16^h\ 34^m$ UT), whereupon they ceased. Henceforth the neon-like glow was confined to the terminal cloud and to two of the knots in the middle third of the train, which was perhaps the region where the glow had its maximum brightness.

As astronomical twilight approached, the train disintegrated gradually, its individual segments tilting away from alignment and forming themselves tile-like upon one another. The small terminal cloud was first to change color as it experienced sunset, becoming orange ($16^h\ 44^m$ UT). The segments of the column followed at $16^h\ 50^m$, when the neon-like glow ceased and the color turned quickly to yellow, to orange, to red. A few seconds later, touched by the mounting Earth-shadow, the segments took on a silvery grey aspect, and soon became invisible against the background of stars ($16^h\ 51^m$).

I was able to take five successive photographs of the meteor train over an interval of eleven minutes, showing the change of its shape, its dissolution, the neon-like glow within the knots, and the drift of the column. Figure 1 shows the second photograph in the series, made at $16^h\ 41^m$. I also measured the positions of the main knot by means of a theodolite which had been kindly lent by Mr. Schumacher, surveys leader for the Board of Works of the city of Lahr i. B. The results are shown in Table 1. The observations were made from this meteorological station (8° 12′ e; 48° 36′ n; elevation, 1164 m).

Using these data, Professor C. Hoffmeister of Sonneberg Observatory has kindly determined the significant elements of the meteoric cloud as follows: Height just before extinction 46 km; distance from Hornisgrinde 289 km; coordinates 4°.3 e and 47°.9 n, in north-central France. The train's drift during the 11 minutes between first and last observation was 20.35 km, corresponding to a wind speed of 31 m/sec, the wind blowing from azimuth 276°. Such a wind speed is not abnormal. *Olivier* [1933] refers to speeds of 20 and 40 m/sec at heights between 88 and 100 km. However, according to *Kahlke* [1921] the predominant direction for heights from 25 to 80 km is an easterly one, veering only at higher levels to a western sector. The height is quite normal, the mean value of the heights of extinction of big

Table 1 – *Results of theodolite observations on main knot of the meteor train*

Time of observation UT		Altitude			Azimuth clockwise from north		
h	m	°	′	″	°	′	″
16	39	7	9	36	257	37	12
16	50	7	48	39	256	22	48

FIG. 1 – The European meteor cloud of November 17, 1955; the main train is seen here by sunlight with two knots having a peculiar neon-like glow; isolated at the right is the explosion point losing its luminescence, showing chiefly reflected sunlight; just below are cirrus clouds and toward the left are stratus clouds

meteors being 49.7 km in the catalogue of von Niessl.

As to the problem of the bright train, *Trowbridge* [1911] reports that normally only meteoric trains at levels as high as 87 km glow, whereas lower objects leave smoky trails that shine by reflected sunlight. In this instance both types appear to be combined. However, Hoffmeister (private communication) believes that a self-luminous glow so strong as to be strikingly seen in conjunction with reflected sunlight is scarcely a physical possibility. He invokes Rayleigh scattering by the finely-divided matter within the train, as a highly probable explanation of the neon-like blue glow. This is supported by the pulsations, regarded as a shadow effect.

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Micro-Tilting Motion of the Ground

In the tiltmetric observation of the ground in shallow-seated observation rooms the tilting motion of the ground caused by rainfall, sunshine, and the like is frequently recorded with predominatingly large amplitudes, disturbing the precise observation of earth tides whose amplitudes are small compared with those caused by the above mentioned sources. But such meteorological disturbances rapidly decrease with the depth of the observation room, and practically the observation at a depth of 100m, for example, below the ground surface is entirely free from the troubles caused by meteorological changes.

In the tiltgrams obtained in a quite deep-seated observation room, very minute changes of an oscillatory character are sometimes observed, their amplitudes being ordinarily less than 0″.01 in angle and their oscillatory motion occurring several times with a period of from about 20 minutes to three hours. These minute and short periodic changes observed may, hereafter, conveniently be called the micro-tilting motion of the ground to distinguish them from the earth tidal changes of larger amplitude (more than 0″.03) and longer period (diurnal and semidiurnal).

These micro-tilting motions of the ground observed in a deep seated room are considered to be caused by various natural phenomena, and, among them, these frequently observed at places close by the sea are correctly interpreted as caused by the change of sea-water load originating from the seiche motion of the neighboring bay, etc. But the nature of the micro-tilting motion sometimes observed at a deep place far remote from the sea is little known in the present stage of investigation. The development of research on these phenomena is considered desirable and may make contributions to the solution of various problems concerning the nature of the Earth and its crust. Under these circumstances the concurrent tiltmetric observation at several deep seated rooms in Japan with highly sensitive tiltmeters of the horizontal pendulum type and with special recording apparatus of open time scale were set up and are, at present, in operation. The results will be reported in detail in the near future, and in the present letter, an example is presented in which a micro-tilting motion was clearly and concurrently observed at two observation stations 90 km apart, along with some interesting and suggestive observations that an earthquake of deep focus and a microoscillation of barometric pressure of particular type were coincidentally observed.

At 05h 57m GMT, November 19, 1954, a strong earthquake of deep focus occurred. Its epicenter, magnitude, and focal depth were estimated to be 41°.0 N and 131°.5 E as shown in Figure 1, 6¾ on the Pasadena scale, and nearly 600 km respectively. The importance of this earthquake is its deep focal depth. Earthquakes having foci of more than 600 km are rarely observed in the neighboring area of Japan. At the same instance of occurrence of this deep earthquake a very conspicuous micro-tilting motion was clearly recorded in the tiltgrams at two observation stations at Kamigamo and Ikuno. The positions of the two stations, 90 km apart, are shown in Figure 1, and copies of the tiltgrams obtained are shown in Figure 2. Moreover, in this case, minute oscillatory changes of barometric pressure of special type were observed at several meteorological observatories; the record of barometric change observed at the Kamigamo Geophysical Observatory is also shown in Figure 2.

The detailed description and discussion on the nature of the present phenomena will be given on another occasion. But, briefly, the amplitudes of micro-tilt and the duration of their oscillation were nearly 0″.02 in angle and ten hours respectively at both stations. The values of pseudo-period of their oscillation were estimated to be in the

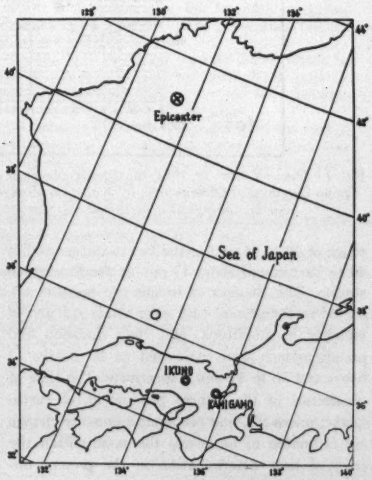

FIG. 1 – The positions of the earthquake-epicenter and the observation stations

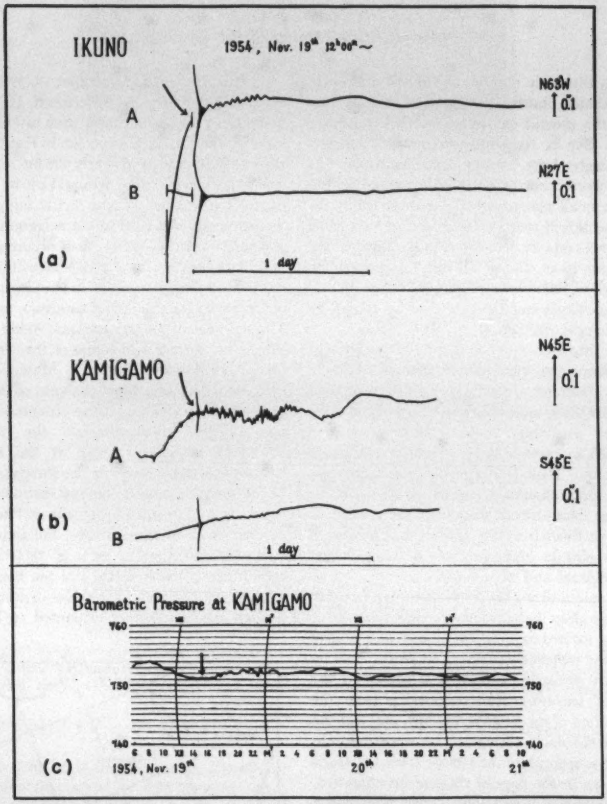

FIG. 2 – Data for Nov. 19, 1954; (a) tiltgram observed at the Ikuno station; (b) tiltgrams observed at the Kamigamo Geophysical Observatory; (c) barogram observed at the Kamigamo Geophysical Observatory; arrows indicate the instant of earthquake occurrence and the commencement of micro-tilting motion

range of 40 to 64 min at the Ikuno station and of 40 to 70 min and about 17 min at the Kamigamo station. The changes of barometric pressure observed in the present case were nearly 0.5 mm of mercury in amplitude, and their duration and pseudo-periods were estimated to be nearly 12 hours and 36 to 54 min respectively. The time of occurrence of these three phenomena of earthquake, micro-tilt, and barometric pressure change are estimated to be nearly the same within the error of time determination in the present observation.

At the present, the cause of the curious coincidence in time of the three phenomena are beyond our comprehension, but it is hoped that the present data may contribute, in the near future, to the solution of the problems of the so-called free oscillation of the Earth and its allied phenomena. A more complete treatment on this problem will be published after the investigation has been pursued further.

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Reviews, Abstracts, and Bibliography

Reviews and Abstracts

U. S. NAVY, CHIEF OF NAVAL OPERATIONS, *Marine Climatic Atlas of the World*, vol. 1: North Atlantic Ocean, NAVAER 50-1C-528, 275 charts, November 1, 1955, $8.00.

This comprehensive atlas was prepared by the U. S. Weather Bureau under contract with the Navy, specifically the Navy Aerology Branch of the Office of the Chief of Naval Operations. The foreword states that the "development of each of the several chart series in the atlas began with the original objective of providing as much meteorological information in analyzed form as practicable from existing raw data." This objective has been achieved and possibly exceeded. Aside from minor criticisms of scale and format, the major criticism of this publication might be its bulk and congestion of data.

It is the most comprehensive publication of its kind to come forth to date. It is based on about 9,000,000 ships weather observations, collected and placed on punch cards by the United States, Germany, the Netherlands, and Great Britain—more observations for the Atlantic alone than had previously been used in atlases for all oceans of the world. (It is probable that some duplication of the collections of these different countries exists, although no indication of the extent of this is given.) (The U. S. Department of Agriculture Weather Bureau *Atlas of Climatic Charts of the Oceans*, published in 1938, was based on about 5.5 million observations for all oceans.) Six hundred fifty thousand observations were used in selected areas for which special detailed graphs, roses, and tables are given.

There are few marine climatological questions that this atlas does not answer. It covers the ocean surface in great detail in 14 series of charts (12 for every month of the year and two for the four seasons) and treats five upper levels in ten chart series by seasons. Seasonal progression and significance of some surface elements do not appear to warrant the detailed monthly treatment used. In addition to two monthly charts of low visibility in combination with winds or cloudiness or both, five different expressions of visibility (three concerned with visibility less than two miles) are given for each month. (The size of type on the first mentioned charts is entirely too small.) Wind aid and wind retard charts, which, within error limits of a few per cent, and certainly to an accuracy consistent with this type of data, are mirror images of one another. It would appear that one chart would suffice for both elements.

Confidence in the information in some of the selected areas is weakened by the relatively low number of observations, fewer than 200 for wind roses with over 30 speed and direction classes, and fewer than 100 for visibility and low cloud amounts in these same areas. The introduction attributes the difference between mean temperature as shown by the isotherm lines and the graphs in northern regions to recent Arctic warming, the graphs being based on the more recent temperature observations. These differences are probably attributable in part to the differences in number of observations from which the isolines and ogives were constructed.

One set of charts that warrants special mention is that on the development and movement of storms. Although the placement of some of the cyclogenesis regions is open to question, especially in the Icelandic-Greenland area, these charts, on the whole, contain excellent information on the frequency of storms, their intensity and generation. Over-printing of storm tracks on these charts rather than on the monthly sea-level pressure charts would have been desirable. Comparison of these tracks reveals little monthly variation.

Following are minor criticisms and comments:

(1) Page vii of the introduction states that 69 pct of the observations give present weather. Page viii states that the Netherlands deck, which consists of 32.6 pct of the total observations used, does not contain present weather. This alone would permit present weather reports in only 67.4 pct of the observations, and it is expected that this would be further reduced by normal omissions of this weather element in other decks.

(2) Lack of smoothing of ogives results in some unlikely frequency distributions.

(3) A brief definition of the 'modified refraction index' would be very helpful to those users not familiar with this term.

(4) The type of binding used inevitably results in wrinkling of the first and last pages. This could be avoided by insertion of a heavier slip sheet between the covers and the first and last pages.

(5) Some indication of the height above sea level of air temperature measurements would have increased the significance and usefulness of the air-sea temperature difference information.

(6) No data are given for Hudson Bay, and too few selected area presentations are given in the rapidly changing region along the Gulf Stream.

(7) The seasonal lag of heating and cooling over water areas argues in favor of shifting the seasons one month later than the periods given in this Atlas.

(8) What the circular wind contingency tables sacrifice in graphic appearance is largely compensated by the amount of detail permitted by this presentation.

BOYD E. OLSON

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Notes and Personalia

Notes

CORRIGENDUM—In the August, 1956, issue of the *Transactions* on page 511 under Notes the information concerning the new Committee on Oceanic Research for the Vice Presidents and General Secretary is in error. The Vice Presidents are Anton Fr. Bruun of Denmark and L. Zenkewitch of the USSR, and the General Secretary is M. N. Hill of England.

CIVIL SERVICE EXAMINATION FOR EXPLORATION GEOPHYSICISTS—The Civil Service Commission has announced an examination for the filling of positions in exploration geophysics located principally in the U. S. Geological Survey with entrance salaries ranging from $3670 to $11,610 a year, GS-5 to GS-15. Information and applications may be secured by writing to the Executive Secretary, Board of United States Civil Service Examiners, Geological Survey, Department of the Interior, Washington 25, D. C.

GEOGRAPHICAL FIELD RESEARCH PROGRAM OF THE NATIONAL ACADEMY OF SCIENCES—The second annual program of geographical research in foreign areas, aided by support provided by the Office of Naval Research, is now in the advanced planning stages. The first program, effective during 1956, provided for ten young Americans to undertake projects for periods up to 14 months to conduct geographical research on topics of their own choosing. Applications should be in the hands of the Foreign Field Research Program, Division of Earth Sciences, 2101 Constitution Avenue, Washington 25, D. C., by December 1, 1956. More mature scholars may submit research proposals to the Geography Branch, Office of Naval Research, Washington 25, D. C.

GRADUATE ASSISTANTSHIPS IN METEOROLOGY AND CLIMATOLOGY AT FLORIDA STATE UNIVERSITY—Several graduate assistantships are available at the Florida State University for the M.S. or Ph.D. degree in Meteorology and Climatology for the academic year 1957–1958. A graduate assistantship carries a stipend of $1740 a year for students holding a bachelor's degree and $2040 a year for students holding a master's degree in meteorology. Students are permitted to carry ten semester hours of formal course work. Applications should be filed as soon as possible and, at the latest, by April 15, 1957. For further information and applica-

tion forms, write to Dr. Werner A. Baum, Department of Meteorology, Florida State University, Tallahassee, Florida.

NEW RADIO ASTRONOMY OBSERVATORY TO BE ESTABLISHED AT GREEN BANK, WEST VIRGINIA—The National Science Foundation has announced that a site near Green Bank about 35 miles south of Elkins has been selected for the location of a radio telescope for which the site requirements are very stringent. It is essential that radio noise or interference of wavelengths below ten meters be at a minimum, and a southerly site was sought to permit viewing of a maximum portion of the Heavens. A valley site is preferred to a hill-top site because of the shielding effect of the hills or mountains to extraneous radio noise. The facility will include initially a 140-foot paraboloid antenna with auxiliary equipment. It is anticipated that the initial cost will be about $3,500,000.

PUBLICATION OF INTERNATIONAL ARID LANDS MEETINGS HELD IN NEW MEXICO IN APRIL AND MAY, 1955—A volume entitled "The Future of Arid Lands" based on the proceedings of the meetings in New Mexico in April and May, 1955, has recently been published by the American Association for the Advancement of Science. This has been edited by Gilbert F. White of the Department of Geography of the University of Chicago. It contains 464 pages, is cloth-bound, and has a price of $6.75 to non-members of AAAS and a price of $5.75 to members. The book contains nearly 40 papers by various authors who took part in the meetings. Address inquiries and orders to the American Association for the Advancement of Science, 1515 Massachusetts Ave., N.W., Washington 5, D. C.

FELLOWSHIPS AND ASSISTANTSHIPS IN METEOROLOGY AND OCEANOGRAPHY AT NEW YORK UNIVERSITY FOR THE ACADEMIC YEAR, 1957–1958—Two fellowships and a number of assistantships are to be awarded for graduate study in Meteorology and Oceanography at New York University for the academic year beginning in September, 1957. Although students are expected to be well grounded in mathematics and physics, candidates need not have taken courses in Meteorology and Oceanography. Recipients of fellowships will devote full time to study toward an advanced degree but may elect one course less than full time and supplement their income by work on research projects. One of the fellowships carries full tuition and fees and a cash stipend of $2500. The second carries full tuition and fees for the nine-month period. Graduate assistantships on research projects are also available, devoting up to about half time on research projects. For information and application forms, address the Assistant Dean in charge of the Graduate Division, College of Engineering, New York University, New York 53, New York. Applications must be completed by April 1, 1957.

COMPARATIVE FIGURES ON SCIENTIFIC PERSONNEL OF THE UNITED STATES AND USSR—The National Science Foundation recently issued the results of a study of scientific and technological education in the USSR which showed that the total number of graduates in science and engineering in that county in 1955 totaled 126,000 of which 59,000 were in engineering. In the United States the total number in the science fields was 59,000 of which 22,600 were in engineering.

MEETING ON ENERGY RESOURCES IN DENVER ON OCTOBER 29–31, 1956—The Denver Chamber of Commerce announces that the first Energy Resources Conference will be held in Denver, October 29–31, 1956. Conference speakers and panelists have been selected from among the men throughout the nation working at the frontiers of development of new sources of energy, including speakers from industry, education, and the government. Interested persons should write to the Energy Resources Conference, % Denver Chamber of Commerce, 1301 Welton Street, Denver 4, Colorado. The registration fee is $35.

NEW OPTICAL ASTRONOMIC OBSERVATORY AT UNIVERSITY OF MICHIGAN—The National Science Foundation has announced the making of a grant of $545,000 to the University of Michigan for the support of studies leading to the establishment of an optical astronomic observatory. There was a previous grant of about $300,000 for this work. The search for a site has been narrowed to about five sites, all located in the southwestern part of the United States where climatic and atmospheric conditions are generally favorable.

NEW RAIN-MAKING METHOD BEING TESTED IN BELGIAN CONGO—A test is being made in the Belgian Congo to determine if an area cleared of vegetation and covered with charcoal will supply the uneven heating required to establish a convection cell, resulting in cumulus clouds that may be a source of precipitation and which may possibly be treated with silver iodide in an effort to induce precipitation.

NEW HYDRAULICS LABORATORY AT THE INSTITUTE OF TECHNOLOGY AT KHARAGPUR—This new hydraulics laboratory, built by the Government of India with aid from UNESCO, is now in operation and is designed especially for the study of waterway construction problems but includes both a teaching and a research laboratory. The laboratory has seven flumes with plate-glass observation windows for aid in studying models of dams, locks, and other installations.

NATIONAL SCIENCE FOUNDATION TO AID IN DISSEMINATION OF TECHNICAL REPORTS OF THE FEDERAL GOVERNMENT—A new project supported by the National Science Foundation with the aid of the Library of Congress and the Office of Technical Services of the Department of Commerce will undertake wider dissemination of significant unclassified technical reports on basic research relating to Government-sponsored scientific work. It is the aim to aid the research scientist to learn what unclassified scientific reports of government research are available in his field of interest, provide him on a subscription basis with a report-announcement service, and provide access to a well-catalogued reference collection. Inquiries should be sent to the Government Research Information Clearinghouse, National Science Foundation, Washington 25, D. C.

1956–1957 COLLOQUIA SERIES OF THE NATIONAL SCIENCE FOUNDATION—A series of ten colloquia in the morning of the first Wednesday of each month will be held in the Board Room of the National Science Foundation in Washington, D. C., relating to various broad aspects of science. Details may be secured by writing to the National Science Foundation, 1520 H Street, N. W., Washington, D. C.

COMPUTATION CENTERS SUPPORTED BY THE NATIONAL SCIENCE FOUNDATION—Grants totaling about $135,000 have been made to five university computation centers in support of their computation work on electronic digital computers. The California Institute of Technology, Massachusetts Institute of Technology,

Oregon State College, University of Washington, and University of Wisconsin have received grants.

ANNUAL MEETING OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS—The Society of Exploration Geophysicists will meet in New Orleans, Louisiana, October 29–November 1, 1956. Details may be secured by writing to the headquarters of the Society, P. O. Box 1536, Tulsa 1, Oklahoma.

GOVERNMENT AID PROGRAMS IN HIGHER EDUCATION—The National Science Foundation in a recent survey has determined that one out of every five graduate students and one out of every six undergraduate students, nearly 390,000 in all, in 1954, received support in one form or another from the Federal Government, with an average cost per student of more than $1000. Of this number, 101,000 were preparing for careers in science, including social sciences. The report is entitled "Federal Support for Science Students in Higher Education."

USE OF METEOR TRAILS IN RADIO COMMUNICATIONS—The Canadian Defense Research Board has announced the development of a new communications technique using meteor trails as a means of transmitting messages over long distances. Project Janet, as it is called, has been the subject of intensive endeavor for four years and has only recently been declassified. It is based on the ionization trails of pin-sized meteors at an elevation of about 60 miles, which ionized particles reflect radio waves. P. A. Forsyth of the Radio Physics Laboratory at Shirley Bay visualized possible potentialities of this system and has directed the work. Experiments have indicated that signals may be transmitted for distances up to 1000 miles.

NEW DEVELOPMENTS ON THE SNOWY RIVER IN AUSTRALIA—The Snowy River in New South Wales, Australia, which drains the Snowy Mountains and flows southerly to the ocean, is to be developed by means of a system of dams, reservoirs, tunnels, and canals so that it will discharge into the arid plains of the Murray and Murrumbidgee Rivers. It will be a combined power and irrigation project utilizing the flow of the Snowy River which averages about 1000 cubic feet per second.

NEW LABORATORY OF THE U. S. FISH AND WILDLIFE SERVICE—A new laboratory especially for the study of fisheries is being constructed by the U. S. Fish and Wildlife Service at Pascagoula, Mississippi. This will be primarily for the purpose of studying methods and techniques of providing high-quality shrimp, oysters, tuna, and other Gulf sea foods. The exploratory fishing vessel *Oregon* of the Fish and Wildlife Service, which operates in the Gulf of Mexico, will be based at Pascagoula.

WORK OF THE *CALYPSO* EXPEDITION—The *Calypso*, the expedition ship of the National Geographic Society, has been working on the making of photographs at depths up to 18,500 feet 350 miles off the Liberian coast, and in the Romanche Trench 500 miles farther west which reaches to a depth of 25,000 feet. The camera developed by Harold E. Edgerton of MIT is being used for this work. It is equipped with electric lights and a position indicator which will determine the distance from the bottom by sonic methods.

NEW RESEARCH SHIP FOR NEW YORK UNIVERSITY—On August 22, 1956, New York University commissioned the research schooner *Action*. This is a 65-foot, two-masted ship. The first studies that it will undertake will be to measure the exchange of energy between the atmosphere and the sea, which is important in problems of weather forecasting. Also, the effect of small ocean waves on radar signals and the study of currents and tides in the New York area will be undertaken.

NEW LARGE-DIAMETER DEEP-SEA CORER—The Lamont Geological Observatory, under the direction of Maurice Ewing, has developed a new deep-sea corer 11½ inches in diameter which will penetrate about one foot of the ocean floor. The large samples secured with this sampler are subject to more precise analysis than cores obtained by smaller instruments. The corer was tested in the Hudson River and in 1300 feet of water off the Canary Islands, and it was used during the summer months in connection with the *Vema's* work in the Mediterranean.

SUBMARINE GRAVITY SURVEY IN THE SOUTH PACIFIC—An 8000-mile gravity survey has recently been completed by Australian and American scientists aboard the British submarine *Telemachus* in the South Pacific. The initial work was started in the area about 250 miles southeast of Sydney and on to the Tonga Trench. The work is being undertaken by the Australian Bureau of Mineral Resources and the Lamont Geological Observatory, and a Vening Meinesz pendulum instrument is being used on the work.

NEW TRAILMARKER FOR POLAR REGIONS—The Research and Development Laboratories of the Corps of Engineers at Fort Belvoir, Virginia, have developed a new electronic technique for marking trails in snow- and ice-covered areas. The system consists of two parallel wires carrying alternating current and a vehicular-mounted radio-type receiver. The device has been successfully tested on the Ice Cap of Greenland and will probably prove valuable in times of poor visibility during the polar night, dense fogs, and snow storms.

NEW THOUGHTS ON THE SATELLITE PROGRAM OF IGY—A meeting in early September in Barcelona, Spain, devoted a day to discussion of the international satellite program. The United States portion, referred to as Project Vanguard, now contemplates that the satellite may attain a velocity of 19,000 miles per hour instead of the 18,000 formerly anticipated. The elliptical orbit would reach a maximum distance from the Earth of some 1500 miles instead of the 800 miles earlier anticipated.

INSTITUTE OF RESEARCH FOR THE NEGEV IN ISRAEL—This Institute is engaged in an intensive research study in an effort to develop the Negev desert region of Israeli for agricultural purposes. Scientists ranging from archaeologists to hydrologists, soil physicists, and botanists are endeavoring to learn the facts about the past cultivation of the area and the extent and distribution of water for use for crops and pastures.

OCEANOGRAPHIC STUDIES OF THE USSR—UNESCO reports that a fleet of more than 30 ships is being equipped by the Soviet Academy of Sciences to carry out oceanographic studies. The research vessel *Akademik Kovalevski* is exploring the coast line of the Black Sea collecting flora and fauna and making chemical analyses of the sea water. Similar work is planned for the Barentz, White, and Caspian seas. Plans for an expedition by the *Vitiaz* in the northeastern Pacific Ocean are well under way.

ARCTIC OCEANIC RESEARCH OF THE *LITKE*—In 1955 the Soviet ice breaker *Litke* made a cruise through the Arctic in which it collected bottom samples from the

ocean, some of which contained extinct organisms never before found in the Arctic. Three bottles dropped in the ocean north of Svalbard have been picked up at various points in Iceland after a drift of some 1200 miles.

MEETING ON FLOOD AND AVALANCHE CONTROL IN YUGOSLAVIA—Problems for protection against and control of floods and avalanches were discussed by the European Forestry Commission of the United Nations Food and Agriculture Organization in Yugoslavia, July 29–August 10, 1956. Spot field studies were made in the mountainous area surrounding the man-made lake of Jablanica in Herzegovina.

WORK OF THE NORTH ATLANTIC WEATHER SHIPS—The nine weather ships stationed in the North Atlantic rescued 52 persons from the sea during 1954. While these ships have facilities primarily designed for the rescue of aircraft casualties, in most cases those saved are survivors from shipwrecks. The ships in this service are supplied by Canada, France, the Netherlands, Norway, Sweden, the United Kingdom, and the United States, and each ship remains on duty three weeks before being replaced by another vessel. Costs are defrayed by various nations in addition to those directly participating in the program. Various programs of oceanographic observations are carried out at the ocean stations, in addition to the regular meteorological observations.

EXPANSION OF THE WORK OF THE UNIVERSITY OF CALIFORNIA AT THE LA JOLLA CAMPUS—Steps have recently been taken to expand the faculty and facilities of the La Jolla campus in connection with Scripps Institution of Oceanography and to provide a graduate program emphasizing science and technology with an undergraduate instruction in support of that program.

NEW ADVISORY PANEL ON THE HAWAIIAN GEOPHYSICAL INSTITUTE—By authorization of Congress, the National Science Foundation has appointed an Advisory Panel on the establishment of a new geophysical institute at the University of Hawaii. The Chairman of the Panel is E. A. Eckhardt of Gulf Research and Development Company, retired. The other members of the panel are: Philip H. Abelson, Carl Eckart, Leo Goldberg, Cecil H. Green, Harry H. Hess, M. King Hubbert, Sverre Peterssen, William W. Rubey, and John C. Warner.

Personalia

WALTER H. BUCHER, Past President of the American Geophysical Union, has become Newberry Professor Emeritus of Geology at Columbia University. In 1955, he was awarded the Leopold von Buch Medal for his outstanding work in geology.

KAZIM ERGIN, who has been the Director of the Geology Department of the Mineral Research and Exploration Institute (MTA) of Turkey for the last three years, has resigned from that post and is now Professor of Applied Geophysics, Mining Engineering Department, Technical University at Istanbul.

PAUL D. FOOTE, Vice President, Gulf Research and Development Company, retired, has been named on a Special Commission of the National Science Foundation on Rubber Research.

GERALD M. FRIEDMAN, formerly Consulting Geologist in Sault Ste. Marie, Ontario, Canada, and Assistant Professor of Geology, University of Cincinnati, has joined the staff of Stanolind Oil and Gas Company as Senior Research Engineer in the Geological Exploration Section at the Research Center, Tulsa, Oklahoma.

WEIKKO A. HEISKANEN, Director of the Institute of Geodesy, Photogrammetry, and Cartography of Ohio State University and AGU's William Bowie Medal winner of last spring, has recently been awarded an honorary doctorate by the University of Bonn.

HARRY H. HESS, Professor of Geology at Princeton University and President of the Section of Tectonophysics of AGU, has been appointed Chairman of the Division of Earth Sciences of the National Research Council for a two-year term beginning July 1, 1956.

JOHN N. ADKINS of the Office of Naval Research has been appointed Chairman-Designate of the Division to serve for the two-year period 1956–1958.

GEORGE H. HICKOX, formerly Program Director for Engineering Sciences of the National Science Foundation, has taken up duties as Director of Research at the Research and Development Laboratories of the Corps of Engineers at Fort Belvoir, Virginia.

H. ARNOLD KARO, Director of the U. S. Coast and Geodetic Survey, has been named a member of the Mississippi River Commission to succeed Leo O. Colbert.

PAUL R. KINTZINGER of the New Mexico Institute of Mining and Technology is now on a UNESCO mission to Egypt conducting research on ground-water problems at the Desert Institute at Heliopolis near Cairo.

CURTIS W. LAMPSON has been appointed Associate Technical Director of the Ballistic Research Laboratories at Aberdeen Proving Ground.

PAUL B. SEARS, Chairman of the Conservation Program at Yale University, was the principal speaker at the annual field day of the Connecticut Agricultural Experiment Station with the "Natural History of Floods" as the title of his address.

EDWARD H. SMITH, Rear Admiral, U. S. Coast Guard, Ret., has retired as Director of the Woods Hole Oceanographic Institution. Columbus O'D. Iselin, who formerly served as Director, has been appointed again as Director.

ATHELSTAN F. SPILHAUS, Dean of the Institute of Technology of the University of Minnesota and U. S. representative on UNESCO's Executive Board, has been appointed by President Eisenhower as Vice Chairman of the U. S. Delegation to the Ninth General Conference of UNESCO to be held in New Delhi, India, in November, 1956.

JOHN S. SUMNER, formerly Professor at Western State College, Gunnison, Colorado, has taken up duties as Manager of the newly established firm, McPhar Geophysics, Inc., to engage in mining and engineering geophysical consulting and contracting throughout the world. The offices are located at 5145 Upton Avenue, S., Minneapolis, Minnesota.

WALTER T. WILSON, Hydrologist, of the U. S. Weather Bureau, will make a hydrologic survey of Turkey during October to December, 1956 under the auspices of the World Meteorological Organization which is affiliated with the United Nations.

WLADIMIR AYVAZOGLOU, retired abstractor and translator, died January 25, 1956. Formerly he had served as translator and editor of Geophysical Abstracts, published by the Bureau of Mines and the U. S. Geological Survey. He was born at Kertch, Cri-

mea, Russia, in 1871. He attended schools in Riga, including the Polytechnic Institute, and completed the civil engineering course in 1893. Subsequently he attended the military school in Moscow, graduating in 1895 and then serving in the artillery. From 1905 to 1909, he studied at the Oriental University in Vladivostok, making a special study of Japanese. In 1910, he took part in a scientific expedition on the living conditions of the population on the Chukchis Peninsula, serving subsequently in the Russian general staff in Russia proper. This work continued until 1917, following which he was attached to the Russian Embassy in Japan, leaving for the United States in 1922. In the United States he served in the intelligence division of the general staff, working as translator. He took up duties with the U. S. Bureau of Mines in 1929, retiring in 1947. He had been a member of AGU since 1932.

JOHN ADAM FLEMING, Honorary President of the American Geophysical Union, and former Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, died July 29, 1956, at the age of 79. A brief biography appears on the opening pages of this issue.

JOHN HAINES GARDINER, District Engineer for the U. S. Geological Survey in charge of Surface Water Investigations in Arizona, died July 27, 1956, at the age of 61. He was born in Philadelphia. He took his baccalaureate degree at the University of Arizona in 1918. For several years he worked on railroad and highway projects, irrigation development, and in 1921 he entered the service of the U. S. Geological Survey. He had been in charge of the work in Arizona since 1938. He had been a member of AGU since 1936.

CARL AUGUST HEILAND, President, Heiland Research Corporation, died February 23, 1956. He was born in Hamburg, Germany. He took his doctorate at the University of Hamburg in 1923. He served as Geophysicist for the State of Hamburg in 1921 and 1922, then worked with the A. Raky Company, 1922–1923, and was put in charge of the Geophysics and Geodetic Department of Askania Werke where he served in 1924 and 1925, becoming their American representative in 1925. In 1926, he took up duties at the Colorado School of Mines where he served as Professor of Geophysics and Head of the Department from 1926 to 1948. He founded the Heiland Research Corporation in 1934. He had been a member of AGU since 1929.

RAYMOND CARROLL OSBURN, Professor Emeritus of Zoology, Ohio State University, died August 6, 1955, at the age of 83. He was born near Newark, Ohio. He took his baccalaureate degree from Ohio State in 1898 and his master's degree in 1900. He took his doctorate from Columbia in 1903, and in 1906 was awarded an honorary doctorate by Ohio State University. He began his career of teaching at Fargo College where he taught from 1899 to 1902. From 1903 to 1907 he taught at the New York High School of Commerce. From 1907 to 1915 he was Assistant Director of the New York Aquarium. From 1915 to 1917, he taught at Connecticut College for Women. He entered work at Ohio State in 1917 and became Emeritus Professor in 1942. In 1945, he became a Research Associate of the Hancock Foundation of the University of Southern California. He had been a member of AGU since 1943.

PEDRO CELESTINO SANCHEZ, Director, Pan American Institute of Geography and History, retired, died March 17, 1956, at the age of 85. He was born at Poanas, Mexico, and was a graduate mining engineer, specializing in metallurgy and geography. He was for many years a leader in science in Mexico in the fields of geography and climatology and devoted some time to teaching in the National School of Engineering. He was elected to corresponding membership in the AGU in 1944.

HUBERT KIRK STEPHENSON, Program Director for the Earth Sciences of the National Science Foundation, died September 2, 1956, at the age of 43. He was born at Youngstown, Ohio, took his baccalaureate degree from Mt. Union College in 1937, and his doctorate from Princeton in 1941. He spent an additional year in study as a National Research fellow at MIT, and in 1942 became connected with the National Defense Research Committee on various wartime problems. From 1944 to 1946, he was with the Office of Scientific Research and Development. From 1946 to 1949, he was a practicing geophysicist, subsequently taking up duties as Liaison Director with the Argonne National Laboratory and with the Test Division of the Los Alamos Scientific Laboratory. He became Program Director of Earth Sciences of the National Science Foundation in 1953. He had been a member of AGU since 1942.

Special Announcements

PUBLICATION OF GEOPHYSICAL MONOGRAPH NUMBER 1, ANTARCTICA IN THE INTERNATIONAL GEOPHYSICAL YEAR—Geophysical Monograph Number 1, entitled Antarctica in the International Geophysical Year, has been published. This is based on a Symposium on the Antarctic held in Washington, D. C., in April, 1956. It comprises about 140 pages. It is illustrated and includes 16 papers by authorities on the Antarctic, with an Introduction by Laurence M. Gould. Also included is a 42″ x 42″ map of the Antarctic compiled by the American Geographical Society from the latest information for use in the current Antarctic planning. The aspects covered include Geographic and Meteorological, Geological and Structural (including Petrology), Upper Atmospheric Physics, Flora and Fauna, and the general program of the U. S. National Committee of IGY in the Antarctic. The authors are: William E. Davies, Carl R. Eklund, Maurice Ewing, Bruce C. Heezen, E. O. Hulburt, Joseph Kaplan, George A. Llano, Finn Ronne, John Roscoe, Morton J. Rubin, A. H. Shapley, J. A. Simpson, Paul A. Siple, Robert P. Sharp, Duncan Stewart, E. H. Vestine, and H. Wexler. The list price is $6.00. Discounts offered: 5–19, 10 pct; 20–49, 15 pct; 50 or more, 20 pct. Address orders and inquiries to the American Geophysical Union, 1515 Massachusetts Avenue, N. W., Washington 5, D. C.

PACIFIC NORTHWEST MEETING TO BE HELD IN SEATTLE, WASHINGTON, NOVEMBER 8–9, 1956—The program for this meeting is now substantially complete, and details may be secured by writing to the Chairman of the Program Committee, Robert T. Beaumont (U. S. Soil Conservation Service, 209 S. W. Fifth Avenue, Portland 4, Oregon).

PACIFIC SOUTHWEST REGIONAL MEETING TO BE HELD IN SACRAMENTO, FEBRUARY 14–15, 1957—Plans are developing rapidly for this annual meeting of the Pacific Southwest Region. The general Chairman for the meeting is Harlowe M. Stafford (U. S. Geological Survey, 2520 Marconi Avenue, Sacramento, California). Harvey O. Banks (Director, Department of Water Resources, State of California, Sacramento, California) is Chairman of the Program Committee and is being aided on the program for the Section of Meteorology by Lloyd H. Magar (U. S. Weather Bureau, Sacramento, California). William R. Gianelli (Department of Water Resources, State of California, Sacramento, California) is Chairman of the Committee on Local Arrangements. Persons interested in the details of the program or in taking part in it should get in touch with the appropriate person.

THIRTY-EIGHTH ANNUAL MEETING TO BE HELD IN WASHINGTON, D. C., APRIL 29–MAY 1, 1957—As announced in the August issue of the *Transactions*, the Thirty-Eighth Annual Meeting will be held in Washington, D. C., April 29–May 1, Monday–Wednesday, 1957. The plans of the various Sections are now getting under way, and it is anticipated that all Sections will have meetings. There will also be general meetings of the Union as a whole, including a Smoker on Monday evening, April 29, a general evening session of the Bowie Medal Award on Tuesday evening, and a general session Wednesday afternoon. Suggestions with respect to any of the Section or Union meetings are invited.

This announcement will also serve as a invitation for members and others to send word of plans for papers to be presented. Titles of papers with three copies of the abstracts should be sent in as soon as possible and not later than March 5, 1957. Please also give information concerning the time required (most papers are allowed from 10 to 20 minutes) and the projection equipment needed. This word should be sent to the office of AGU at 1515 Massachusetts Avenue, N. W., Washington 5, D. C., or to the Secretary or Program Chairman of the appropriate Section, as follows:

Geodesy, Frank L. Culley or Donald A. Rice (Program Chairman), U. S. Coast and Geodetic Survey, Washington 25, D. C.

Seismology, James A. Peoples, Jr., 39 Edgewater Drive Waltham 54, Massachusetts.

Meteorology, Woodrow C. Jacobs, 3812 Nash Street, S. E. Washington 20, D. C.

Terrestrial, Magnetism and, Electricity, Robert E. Gebhardt, U. S. Coast and Geodetic Survey, Corbin, Virginia.

Oceanography, Donald W. Pritchard, Chesapeake Bay Institute, Route 2, Box 42, Annapolis, Maryland.

Volcanology, Geochemistry, and Petrology, Leroy T. Aldrich, Department of Terrestrial Magnetism, 5241 Broad Branch Road, N. W., Washington 15, D. C.

Hydrology, Ralph N. Wilson, 3322 Stanford Drive, University Hills, West Hyattsville, Maryland, or Bernard Frank (Program Chairman), 2807 Washington Avenue, Chevy Chase 15, Maryland.

Tectonophysics, Benjamin F. Howell, Jr., Dept. of Geophysics and Geochemistry, Pennsylvania State University, University Park, Pennsylvania.

As Section Secretaries reserve the right to close filled programs in advance of the dates indicated, please make it a point to send word in early. Abstracts of the papers are published in the program. Remember that an abstract is an opportunity to bring the important results of your work to all those that see the program. The abstract should be concise but comprehensive and informative and must not exceed 200 words. Longer abstracts will be reduced to 200 words or omitted at the editor's discretion. Complete manuscripts are not necessary but are desired and should be forwarded to the office of the Union by April 15 in order to be available for science news writers. Please indicate whether the paper is being submitted for the program only or also for consideration for publication in the *Transactions*. (Papers for publication only are also welcome for consideration for the *Transactions*.) If a paper is written in collaboration, please indicate by whom it will be presented. Arrangements can usually be made with the Section Secretary or Program Chairman for the presentation of papers by authors who are unable to attend, but papers to be presented by title only are not included in the program.

Make hotel or room arrangements directly with the hotel of your choice at an early date. If you fail on the first attempt, bear in mind that advance bookings that are not taken up are cancelled two weeks in advance and that a follow-up request in mid-April may bring the desired response. We are making block bookings at three hotels again; an announcement regarding these will appear in the Special Announcements in the December issue of the *Transactions*.

ELEVENTH GENERAL ASSEMBLY OF IUGG TO BE HELD IN TORONTO, CANADA, SEPTEMBER 3–14, 1957—This is simply a brief reminder note calling attention to the announcement that has appeared in previous Special Announcements. Word indicates that the various Associations are rapidly formulating their plans for this triennial meeting. Any who desire to take part in this meeting either in the way of presentation of papers or just the matter of attendance should advise the office of AGU promptly. A copy of your note to the AGU office should be sent to the appropriate Section Secretary (see name and address in the above announcement concerning the Thirty-Eighth Annual Meeting of AGU).

PUBLICATIONS OF IUGG AND ITS ASSOCIATIONS—Attention is called to the fact that the *Bulletin d'Information de l'U.G.G.I.* or the *I.U.G.G. News Letter* may be secured on a subscription basis at the rate of $8.50 per calendar year. Subscriptions should be sent to Butterworths Scientific Publications, 88 Kingsway, London, W.C. 2, England. In addition to containing pertinent information regarding the IUGG, the Bulletin contains material relating to world-wide aspects of geophysics, considerable information on the international activity in IGY, and an occasional scientific paper.

Bulletin Geodesique of the Association of Geodesy is likewise available on subscription from the same company at a price of $5.60 per calendar year. The Proceedings of the Tenth General Assembly of the International Association of Meteorology, held in Rome in September, 1954, is also available from Butterworths at a price of 80 shillings plus postage. This contains 594 pages and includes about 100 papers presented at the meeting in Rome.

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A Statistical Analysis of Hiran Measurements

JOSEPH L. STEARN AND ERNEST J. PARKIN

Abstract—The Hiran electronic distance-measurement system is described, and the problem of defining rejection limits on observations is introduced. A number of samples of actual measurements is analyzed statistically by means of significance tests, and suggestions made for a new approach as to the rejection and acceptance of observations.

General—Shoran is an electronic navigation system which was developed during World War II to take advantage of the accuracy of radar ranges. Signals from the transmitter component of the Shoran equipment aboard a ship or plane excite two fixed ground sets or transponders located at accurately known positions, causing them to relay signals back to the craft. The receiver component then translates the elapsed time into the distances between the vessel or aircraft and the two ground stations. The craft's position is then established at the intersection of the two circles of position centered at the fixed transponders.

Excellent results were obtained with Shoran equipment in navigating an aircraft into the proper position for bombing a predetermined target during periods when, because of weather conditions or darkness, the target was not visible from the aircraft. This navigation is accomplished by having the radar ranges of the target from each of two ground stations precomputed. The aircraft flies a circle at the computed distance around one of the ground stations known as the 'drift' station. When the second distance indicator shows the precomputed distance of the second ground station, the 'rate' station, the bombs are released.

The success achieved by the use of Shoran in this type of mission suggested the possibility of its use as an instrument for measuring distances in geodetic surveys. The bombing-type Shoran equipment has been modified to obtain the higher degree of accuracy required in geodetic work. This high precision equipment is called Hiran.

Electronic measurement—In this operation the aircraft flies across the line it is desired to measure, continuously recording the slant ranges from the aircraft to each of the two ground stations. These distances appear on the mileage dials on the instrument panel as the operator manipulates the controls. At the point when the sum of the two distances is a minimum, the aircraft is in the vertical plane through the ground stations.

The recording is done by a 35-mm motion-picture camera which photographs the instrument panel at regular intervals of two seconds. These films brought back by the pilot are the raw data for the crossing measurement.

During early tests crossings were flown perpendicular to the line between stations. This meant that during the approach the distances to the ground stations were decreasing until the plane reached the line. Then, at the instant of crossing, the trend reversed direction and the distances began to increase as the plane left the line. The Shoran operator during this period was manipulating two controls, both of which reversed direction at the instant of crossing. It was found that the sum of these distances gave a very ragged curve when plotted against time.

To remedy this defect, the direction of crossing was changed to make an angle with the perpendicular so that the distance to one station was increasing while the distance to the other was decreasing at the instant of crossing. This procedure gives much smoother distance-time curves.

A mission consists of twelve separate line crossing measurements, six at each of two different flying altitudes, generally about 1000 ft apart.

Computations—The first step in the reduction of the raw data from the films is the computation of the 'minimum sum.' The values of the two distances on each frame of the film to the two ground stations are listed and summed. These observed data are plotted against time, fitted to a parabola, and the minimum of the curve obtained. This value, called the 'minimum-sum distance,' is the sum of the uncorrected ray-path distances from the aircraft to the two ground stations.

The timing and velocity corrections are applied to reduce this minimum-sum distance to the true ray-path distance. The geometric correction then reduces the true ray path distance to the spheroidal distance.

The timing correction is a correction for drift of the instruments. Four sets of observations of the airborne zero dial readings are taken, one at the beginning and end of each altitude group.

In order to measure distances a certain velocity is built into the instrument since the instrument is fundamentally a device to measure travel time. Because the actual velocity varies with temperature, pressure, and moisture content of the atmosphere, a velocity correction must be applied. This is computed from the data obtained from atmospheric soundings.

The geometric correction depends upon the ray-path distance, the elevations of the two ground stations, the flying altitude, and the dimensions of the reference spheroid.

After applying these corrections there are in general twelve measurements of the line distance known as a mission. Six measurements are taken at each of two different altitudes. Means of the two altitude groups are computed, and finally a mean of these two values gives the observed value of the distance to be used in the adjustment of the net.

Until 1955 the criteria used by the Air Force computing personnel for the acceptability of a mission were:

Criterion 1—The difference between the means of the two altitude groups shall not exceed 0.0030 mile.

Criterion 2—No line crossing shall deviate from the group mean by more than 0.0030 mile.

The specifications issued in June 1955 retained Criterion 1 without change. Criterion 2, however, was relaxed somewhat so that no more than two line-crossing measurements could deviate from the mean by more than 0.0030 mile.

These criteria were rules of thumb which had been determined from the experience of those connected with the tests of the Hiran equipment and the projects accomplished up to this time. Now that a large amount of data has accumulated it is possible to re-examine the criteria from a statistical standpoint.

It is the purpose of this paper to make a statistical analysis of a number of missions in order to suggest reliable methods for making decisions on acceptance or rejection of missions. The missions under consideration are measurements made by the U. S. Air Force during the progress of the Florida-Puerto Rico-Trinidad Hiran Survey.

1. Student's $t = \dfrac{\bar{x} - \bar{x}'}{s\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$

2. $F = \dfrac{s^2}{s'^2}$

3. Sukhatme $d = \dfrac{\bar{x} - \bar{x}'}{\sqrt{s^2 + s'^2}} = t' \cos\Theta - t \sin\Theta$

$\tan\Theta = \dfrac{s}{s'}$

4. $F_{V.A.} = \dfrac{s_b^2}{s_w^2} = \dfrac{\text{Between Group Mean Square}}{\text{Within Group Mean Square}}$

FIG. 1 – Formulas for significance tests

Statistical analysis—In making a statistical analysis of the missions which have been chosen for study we shall make use of several significance tests indicated by formula in Figure 1. In the formula for t, the symbols have the following meanings

$\bar{x}$, mean of the first sample or altitude group;

$\bar{x}'$, mean of the second sample or altitude group;

s, pooled standard deviation of the mission;

n_1, n_2 number of measurements in samples 1 and 2.

In the formula for F, s^2 and s'^2 denote the variances of samples 1 and 2 respectively.

Let us consider the following criteria for mission acceptance, both of which must be satisfied:

Criterion 1—The difference between the means of the two altitude groups should not exceed 0.0030 mile.

Criterion 2—The deviations of at least four line crossings from the group mean should not exceed 0.0030 mile.

First examine Criterion 1. This limit of 0.0030 seems reasonable and consistent with statistical theory. If we assume the probable error of a mission obtained from the average deviation of individual missions from the mean of a number of missions over the same line to be about 0.0015, the standard deviation would be 0.0022. Making use of the formula for Student's t (see Fig. 1), we have

$$t = \frac{\bar{x} - \bar{x}'}{0.0022\sqrt{1/6 + 1/6}}$$

Now in order for a mission to be acceptable statistically, using the t-test at the five per cent level of significance and for ten degrees of freedom, $t = 2.228$. This value is obtained from a table of percentage points of the t-distribution [*Pearson* and *Hartley*, 1954, Table 12]. Solving for $\bar{x} - \bar{x}'$ gives

0.0028. With the five per cent level of significance, the probability of t falling outside the limits of -2.228 and $+2.228$ is 0.05. Criterion 1 thus may not cause us to make the wrong decision as to acceptance or rejection of a mission.

Now the imposition of Criterion 2 in rejecting a mission which meets acceptance on basis of Criterion 1 puts undue restraint upon the acceptability of the observations. From the formula for Student's t, it can be seen that a relatively large standard deviation may be necessary in order to indicate the existence of no real differences between means in a mission.

Rejecting a mission whenever measurements in either sample differ from the mean by more than 0.0030 can result in the wrong decision because such deviations can exceed 0.0030 without the standard deviation exceeding 0.0022.

In practice, however, the application of one or more statistical tests will enable one to make decisions as to acceptance, rejection, or conditional rejection with the final decision deferred until the mission is reflown and analyzed.

Example of the application of the tests—To illustrate the application of the tests, two missions, 3 and 3A, are worked out in detail (Table 1). Mission 3 was rejected on the basis of Criterion 2. Mission 3A is the reflight over the same line. Note that only the decimal part of the mileage is shown.

From Table 12 [*Pearson* and *Hartley*, 1954] we find that the probability of $t = 0.70$ (Mission 3) for ten degrees of freedom is about 0.5. This shows that the two samples could well have come from the same population; that is, that there is no significant difference between the means of the two altitude groups. The mission can therefore be accepted on the basis of the t-test. The corresponding value for Mission 3A also indicates acceptance.

Table 1.—*Analysis of two tests*

Mission 3				Mission 3A			
First alt.		Second alt.		First alt.		Second alt.	
Dist.	Dev.	Dist.	Dev.	Dist.	Dev.	Dist.	Dev.
0.5916	0.0002	0.5870	0.0061	0.5958	0.0015	0.5952	0.0001
0.5860	54	0.5904	27	0.5943	0	0.5971	20
0.5937	23	0.5921	10	0.5974	31	0.5954	3
0.5903	11	0.6006	75	0.5887	56	0.5950	1
0.5936	22	0.5904	27	0.5967	24	0.5911	40
0.5930	0.0016	0.5980	0.0049	0.5931	0.0012	0.5970	0.0019
$\bar{x} = .5914$		$\bar{x}' = .5931$		$\bar{x} = .5943$		$\bar{x}' = .5951$	
Mean = 0.5922				Mean = 0.5947			
$\bar{x} - \bar{x}' = -0.0017$				$\bar{x} - \bar{x}' = -0.0008$			
$s = 0.0042$				$s = 0.0027$			
$t = 0.70$				$t = 0.51$			
$F = 3.09$				$F = 2.13$			

TEST	HYPOTHESIS	OBJECT: TO DETERMINE
Student's t 2 groups	$\mu_1 = \mu_2$ It is known that $\sigma_1^2 = \sigma_2^2$ but value is unknown.	If 2 samples belong to same population.
F 2 groups	$\sigma_1^2 = \sigma_2^2$	If no real differences exist in sampling errors.
Sukhatme d 2 groups	$\mu_1 = \mu_2$ $\sigma_1^2 \neq \sigma_2^2$	If 2 samples come from populations with same mean but different variances. If the difference between the means could arise from the difference of the variances.
V.A. 4 groups	$\mu_1 = \mu_2 = \mu_3 = \mu_4$	If no real differences exist in group means.

FIG. 2 – Purposes of significance tests

A table of percentage points of the F-distribution [*Pearson* and *Hartley*, 1954, Table 18] is used to interpret the values of F computed for the two missions. In both cases, F is considerably less than the value of 5.05 given in Table 18 [*Pearson* and *Hartley*, 1954] for five degrees of freedom in each

TABLE 2 – *Results of analysis of rejected and reflown Hiran missions*[a]

Mission	Rejection limit criteria	t test	F test	d test	VA test
1	r	r	a	r	
1A	a	a	r	a	r
2	r	a	a	a	
2A	a	a	r	a	a
3	r	a	a	a	
3A	a	a	a	a	a
4	r	a	a	a	
4A	r	a	a	a	r
4	r	a	a	a	
4B	a	a	a	a	a
5	r	a	a	a	
5A	a	a	a	a	r
6	r	a	a	a	
6A	r	r	a	r	r
6B	a	a	a	a	

[a] The letter r indicates rejected; a, accepted.

TABLE 3 – *Results of analysis of accepted missions*

Mission	Rejection limit criteria	t test	F test	d test
7	a	r	a	r
8	a	r	r	r
9	a	r	a	r
10	a	r	a	r
11	a	a	a	a
12	a	r	a	r
13	a	r	a	r
14	a	r	a	r

sample. Both missions will therefore be acceptable on the basis of the F-test. For the hypothesis of a given test and the conclusions to be derived from the test (see Fig. 2).

A significance test known as the Sukhatme d-test is used where the variances of two samples are not taken to be equal. For equal sample sizes the quantities d and t are identical. The d-test, unlike the t-test, can indicate that the samples belong to populations with the same mean but different variances. The t-test takes the variances equal so that we might be led to reject the hypothesis when we should accept it. A somewhat large t can be due to the differences in the variances and not the means. To overcome the objection that the t-test is not sufficiently sensitive to possible discrepancies in the variances, the Sukhatme d-test can be used, comparing the computed d with the tabular d [Sukhatme, 1938, Table 2] at the five per cent level of significance.

Results of analysis—Fourteen Hiran missions over six lines were analyzed by the use of significance tests. The results are given in Table 2. The original flight is indicated by number alone. The first reflight is indicated by the letter A and the second reflight, if made, by the letter B. All of the six original measurements as well as two reflights, 4A and 6A, were rejected. Missions 1 and 6A were rejected on the basis of Criterion 1, Missions 2, 3, 4, 5, and 6 on Criterion 2, and 4A on both criteria. It should be noted that, in the case of the five rejects on Criterion 2, these are all acceptable when significance tests are applied. The two rejects on Criterion 1 are confirmed by the significance tests. The one reject on both Criteria 1 and 2 is acceptable by the significance tests; this can be explained by the fact that the mean limit was exceeded by only 0.0006.

Where a mission of two groups of six observations each is not accepted and not rejected, but held for further testing with additional observations, we may perform a variance analysis test of the combined missions of four groups in order to determine possibly if no real differences exist in the group means.

Table 3 shows the results of a study of eight missions in which the limit of 0.0030 used in Criterion 1 was approached (0.0026 to 0.0029). One mission definitely indicates the desirability of a reflight. Whether or not additional observations should be made and analyzed along with the original observations for any of the other missions would depend upon cost and time factors.

Conclusions—The results of significance tests indicate that wrong decisions may be made on the basis of preassigned criteria for acceptance of Hiran observations. Criterion 1 will not conflict with the results indicated by significance tests. Criterion 2, however, rejects, and consequently requires reflights of, missions which by the application of significance tests are acceptable.

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Standardization of the World's Gravity Data

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Abstract—The problems of gravity standardization are discussed from the standpoint of absolute determinations, relative measurements of gravity on a world wide scale for calibration and reference purposes and internal national networks. Work is in progress to improve present standards; in particular, the pendulum program that has been carried out under the auspices of the Air Force Cambridge Research Center and which is being extended as part of the International Geophysical Year program is discussed. The extent of the world program of gravimeter measurements for evaluating present standards, which has been carried out under the auspices of the Office of Naval Research, and a program for the development of an internal network of gravity bases at the principal airports in the United States for use in coordinating and integrating gravity data taken by various groups in this country are presented.

Introduction—The problem of standardizing the world's gravity data can be divided into three parts: (1) the establishment of an accurate absolute-gravity reference datum, (2) the establishment of a gravity reference standard for evaluating the accuracy of relative gravity measurements, (3) the establishment of an international network of gravity base stations so that all of the world's gravity data can be integrated into a unified whole. To some extent these objectives have already been met.

By international agreement the absolute gravity determination of *Kühnen* and *Furtwängler* [1906] at Potsdam, Germany, was adopted early in the century as a world reference datum. A world network of gravity control bases has been developed through direct and indirect gravity connections between the various national gravity-base sites and Potsdam. All internal national networks of gravity bases have also been put on the Potsdam datum through connections to the national base sites. By using only pendulums in making these observations, accurate relative measurements were believed assured.

However, it is now generally agreed that the Potsdam base value adopted is in error, possibly by as much as 18 mgals. In addition, *Morelli* [1946] and *Hirvonen* [1948] have shown that there is considerable uncertainty regarding the accuracy of the various national gravity base values in use. It also has been shown by *Woollard*, *Harding*, and *Rose* [1955] that the national reference networks of gravity bases are not sufficiently accurate to meet modern requirements as a reference standard. These investigators also called attention to the fact that several gravity reference standards are being employed, not only locally but also on studies of international and world-wide scope. In brief, there is evidence that there is a very real problem of gravity standardization. Until it is resolved many geoidal studies, in particular those being undertaken by the Mapping and Charting Laboratory of Ohio State University will be handicapped if not partially bereft of significance.

Current investigations on standardization; absolute gravity— Since the Potsdam determination of absolute gravity, *Heyl* and *Cook* [1936] have made a new determination at the National Bureau of Standards in Washington, and *Clark* [1939] also has made a new determination at the National Physical Laboratory in Teddington, England. On the basis of relative measurements between these two sites by *Browne* and *Bullard* [1940] with pendulums and by *Woollard* [1950] with gravimeters, it appears that these later absolute gravity measurements may be accurate to better than five mgals. Either would thus give a better absolute datum than the Potsdam value now in use. However, since the approximate error in the Potsdam base value is known, little would be gained by a change in datum at this time, particularly in view of the current activity towards obtaining a more accurate absolute gravity value. At present there are nine experimental determinations of absolute gravity in progress mostly based on the observed acceleration of falling bodies. This procedure is in contrast to the pendulum period method used in the earlier measurements. While some of these later experiments have been in progress now for a number of years, as yet there are no definitive results that would indicate these techniques are superior to the pendulum period method.

International Gravity Reference Standard—In 1948 the author [*Woollard*, 1950] made an extensive series of gravity measurements on a global

basis using the prototype of what is now referred to as the Worden geodetic gravimeter. One objective of this trip was to evaluate the accuracy of this gravimeter using the national gravity base values as a standard, and, at the same time, checking the national gravity base values for marked errors. Another objective was to evaluate the degree of agreement between the calibration furnished with the instrument by the manufacturer and that determined experimentally from the reoccupations of the various national base stations. It was shown that while some of the base values did appear to be in error by a few mgals, on the whole the values in use agreed to within one mgal with those determined with the gravimeter. The difference in calibration standard was found to be sufficient to give variations of two mgals for 1000 mgals change in gravity.

While these results did indicate that a gravimeter could be used for intercontinental geodetic studies and that there were few significant discrepancies in values at the national gravity bases occupied, there was still some question as to how accurately the gravimeter had portrayed the gravity field away from the base network, particularly in areas of high and low latitude where the spring system was at points of maximum elongation and compression respectively. The problem of an accurate gravity reference standard for use both as a basis of calibration and as a means of checking the linearity of response of the spring system was therefore regarded as of prime importance.

As a first step on this problem, extensive tests were made to determine gravimeter response characteristics; then field tests were run using data obtained with different pendulum systems as standards of calibration. The results [*Woollard*, *Harding*, and *Rose*, 1955] showed that the Cambridge University (England) pendulums and the quartz pendulum apparatus developed by the Gulf Research and Development Co. gave the least scatter in values and also gave results most closely in agreement. However, a calibration based on results with these pendulums differ significantly from that based on the national gravity base values used in the 1948 measurements. This difference is significant since a large part of the Earth was and still is being studied gravitationally by groups such as Expeditions Polaires Françaises using gravimeters calibrated against the same national gravity base values in western Europe used by the writer for his 1948 measurement. The adoption of first the Cambridge pendulums and later the Gulf pendulums as a standard of calibration by the writer for global gravity studies has given rise to the so-called 'European milligal' and the 'American milligal.' Such a division on geographical grounds is of course physically meaningless.

While the Gulf-Cambridge pendulum standard has not been finally formalized, work has reached the final adjustment stage. The program in setting up this standard was initiated in 1949 when it became apparent that existing standards of calibration were not good enough to assure gravimeter values accurate to within six mgals in either the polar or equatorial regions. Under the sponsorship of the Cambridge Airforce Research Center, a series of thirty measurements were made in 1951 cooperatively by the University of Wisconsin and the Lamont Geological Observatory of Columbia University between Mexico City and Fairbanks, Alaska, using a set of Gulf pendulums on loan to the latter organization. However, because of difficulties in radio reception for determining time, and manometer troubles, the accuracy of this series of measurements was limited to about one mgal. In 1953, through the cooperation of the Gulf Research and Development Co., the measurements were repeated using two other sets of Gulf pendulums and with improved pressure and chronometer units. The internal consistency of these data indicated an average accuracy of 0.3 to 0.5 mgals. In 1954 the central sector of the line of measurements was again occupied to determine the degree to which the earlier measurements could be repeated. The results of these various measurements and the problem of pendulum measurement in general have been discussed by *Woollard*, *Rose*, and *Bonini* [1956]. Comparative measurements at the same sites were made by the Dominion Observatory of Canada using the Cambridge University pendulums in 1952 and 1953 [*Garland*, 1953, 1955] and key sites were occupied also by the U. S. Coast and Geodetic Survey in 1952 and 1953 using the Brown pendulum apparatus. It is significant that the three sets of pendulums showed excellent agreement over the entire range although they are markedly dissimilar. The Gulf pendulum apparatus consists of two quartz, non-magnetic pendulums which are swung simultaneously 180° out of phase with each other. They are maintained in a sealed case throughout a survey, are operated at constant temperature and the case medium is ionized with a radioactive salt to conduct off induced electrostatic charges developed on the pendulums. The Cambridge pendulums are of the same operational design as

the Gulf pendulum apparatus with two pendulums swinging on the same support 180° out of phase, but they are made of Invar and must, as a result, be swung in a constant magnetic field. This is done through the use of a Helmholtz coil. No attempt is made to swing at constant temperature or with a constant viscosity of the medium inside the case. Instead of a single pair of pendulums, several interchangeable sets of pendulums are used at each observation site. The Brown apparatus is a single pendulum system and a correction must be made for induced sway in the support. An Invar pendulum is used and this must be swung in a constant magnetic field as with the Cambridge pendulums. Observations are made with two pendulums at each site, at varying temperatures and with varying viscosity of the medium in the case.

In view of the agreement in results between these three sets of pendulum apparatus in North America, a second series of pendulum measurements for standardization purposes was established in 1955 between Oslo, Norway, and Capetown, South Africa. In part, these measurements are duplicated by observations with the Cambridge pendulums. An additional series of similar pendulum control bases is planned from Thule, Greenland, to Cape Horn, South America, following the east coast of North and South America. Similarly, an extension of the Alaska-Mexico line is also planned down the west coast of South America to Santiago, Chile. A fourth series is planned from the Aleutian Islands via Japan through Australia to Antarctica. The last would follow the existing line of bases already established with the Cambridge pendulums in Australia and New Zealand.

It is believed that the completion of the above program, which will be part of the United States gravity program for the International Geophysical Year, will give a firm basis for an international gravity reference standard. With time, as other observers make additional pendulum and gravimeter measurements at the same sites, the accuracy of the standard should improve. Figure 1 shows the location of these reference standard pendulum bases established to date and those planned for the future.

An international network of control bases—A program to establish an international network of gravity-control bases was started under the auspices of the Office of Naval Research by the writer in 1948 at the same time the accuracy of the various national gravity bases was being investigated. Most of the problems uncovered on standardization and other problems in geodetic gravimeter work not suspected or critically evaluated before, were a direct outgrowth of this study and have been discussed by *Woollard* and *Bonini* [1955]. While the program is no longer supported by the Office of Naval Research, credit should go to this organization for sympathetic support and understanding during that period in which it appeared that much of the work on setting up an international network of gravity control bases would go for naught because of the problems encountered. Now, eight years after the program was started, the data for some 3500 bases in 85 countries are being reworked to conform to better methods of reduction, and a more accurate calibration standard.

Most of the base observations established under this program have been dual occupations because of idiosyncrasies in the original instrument that were not appreciated at the beginning of the program. Some areas, notably South and Central America, still require checking. Other areas have not been studied at all or only in a cursory fashion because either there were local gravity programs in progress or because the area was politically inaccessible. Unfortunately, a very large segment of the Earth has been and still is in the latter category. However, it is hoped that during the International Geophysical Year it might be possible to arrange for sufficient measurements in these closed areas to permit known extensive compilations of local data to be evaluated and integrated into the world network.

Since accessibility is a prime factor for all reference bases, the bases of the international network have been located principally at airports. Similarly, the pendulum series of measurements established as a calibration standard have been located either at airports or tied by gravimeter connections to the local airports. In this way calibration runs with gravimeters can be conducted using continuing flights with the check observations made during the few minutes that the plane is on the ground. Figure 2 shows the location of the principal international gravity bases established to date.

National gravity control networks—In most countries there is a national network of pendulum gravity-control bases that has been established by some governmental agency such as the U. S. Coast and Geodetic Survey in the United States. However, as has been indicated, the average accuracy of these gravity base networks, established for the most part over a fifty-year period with different observers and with different instruments is not

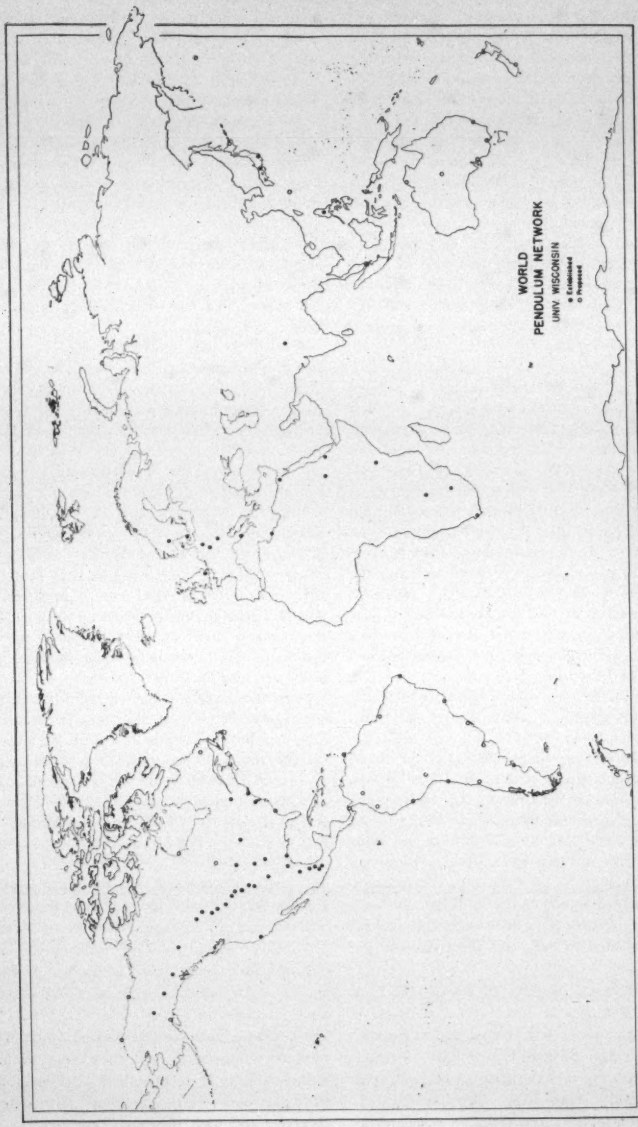

FIG. 1 - World Pendulum gravity standardization network

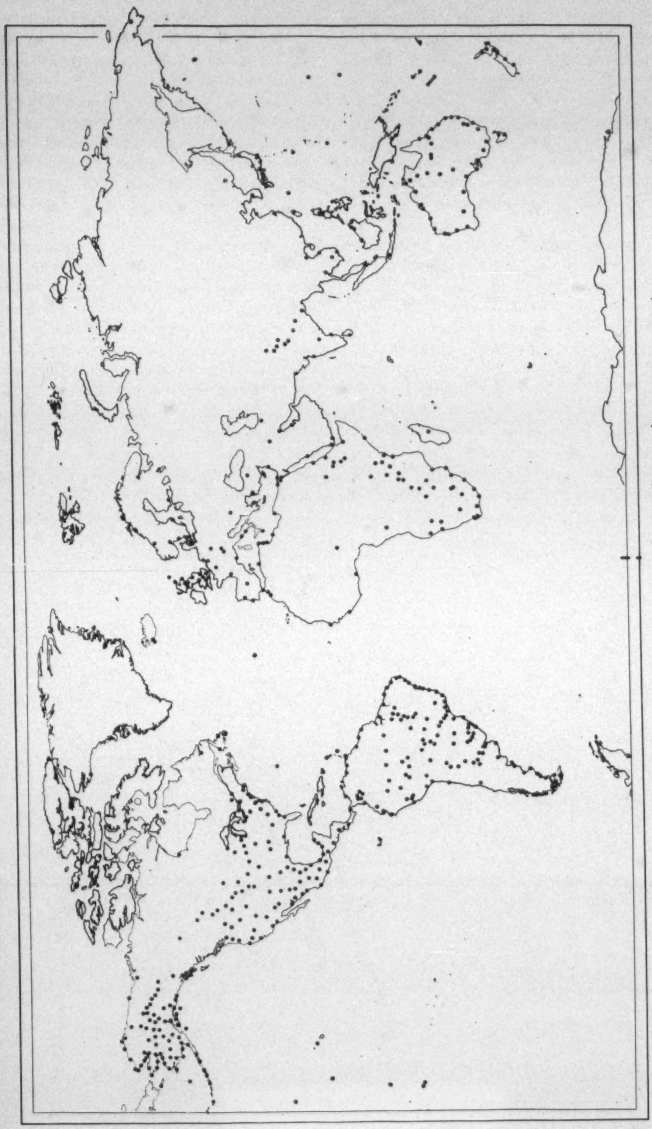

FIG. 2 – World network of gravity control station based on gravimeter measurements

apt to be sufficient to meet modern requirements. In the United States a partial evaluation of the national base network has been possible through the observations made in connection with oil exploration and university studies concerning regional geology and crustal structure. The significance, however, of these check observations has been no better than the calibration standard employed. The author's studies have shown variations of as much as eight mgals per 1000 mgals change in standards being used. For geophysical studies on a nationwide basis such as those sponsored by the Special Committee for the Geological and Geophysical Study of the Continents of the American Geophysical Union, which are in part based on compilations of oil company gravity data, it has been found expedient to establish a new set of gravity control bases in order to integrate all the data. These have been established at the principal airports since the observation can be made on continuing airplane flights and it is easy to cross check by using series of scheduled north – south and east – west flights. On the basis of closures on interconnecting loops, it appears that an accuracy of about 0.2 mgals is being realized. To date data for over 150 sites distributed throughout the country have been taken. This work was done in less than six weeks working time and with a minimum of expense since much of it was done in connection with trips made for other purposes. Figure 3 shows the location of these bases established so far. Such an internal network of control bases in any country, or even for an area the size of Europe would materially aid in the standardization of gravity values.

Integration of land and marine gravity work— While efforts have been made by all observers of gravity at sea to tie their measurements to land based control points, there frequently appear to be discrepancies in these connections. The best procedure for such ties would seem to be that adopted by the Lamont Geological Observatory, that is, using a gravimeter for making connections between dockside submarine gravity stations and land gravity bases. In the absence of a gravimeter it would appear better to have some other group make a gravimeter connection, at possibly a later date, than to dismantle the submarine pendulum equipment and transport it to a land site. As has been shown by *Woollard*, *Harding*, and *Rose* [1955

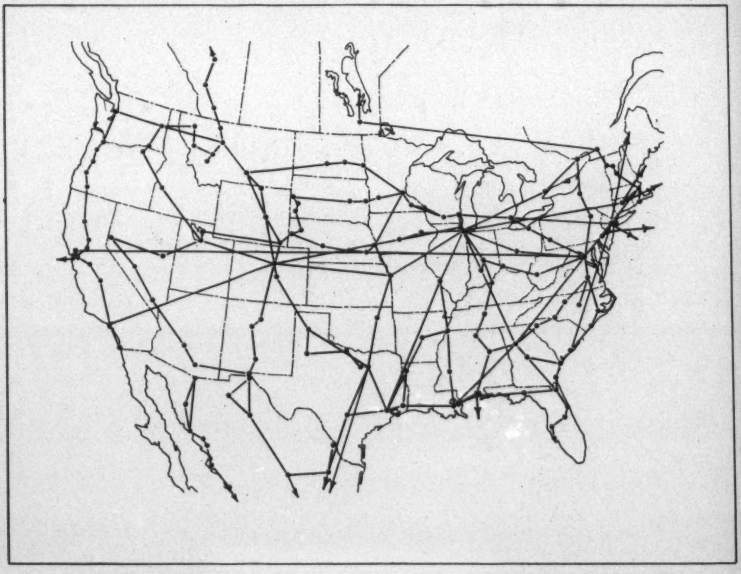

FIG. 3 – Network of gravity control stations at airports in the United States

the average accuracy of the Vening Meinesz port stations throughout the world is about ±4 mgals, with a few stations departing by 10 mgals or more. This, however, cannot be said to represent the average accuracy of submarine gravity work since port stations are the worst sites possible. This is because the submarine must of necessity be surfaced, and, because of the swell of passing vessels, the ship is apt to rub or bump against the dock. Furthermore, environmental conditions, particularly temperature, may be markedly different from those encountered at sea. With the introduction of submarine gravimeters, which presumably will be more portable than the pendulum equipment, it should be possible to improve the integration of marine gravity work with land work by making dockside measurements actually on land rather than aboard the submarine.

Summary—The writer feels that a program for gravity standardization is well advanced and that it is quite possible that by the end of the International Geophysical Year most of the major obstacles to standardization will have been surmounted, with the possible exception of having an absolute gravity datum accurate to one mgal or better.

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A Study of the Ionization Produced in Various Gases by Cosmic Radiation

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Abstract—To study the ionization produced in various gases by cosmic radiation, four geometrically similar brass chambers differing greatly in size were used with the Gish-Sherman ionization apparatus. Each of the chambers filled with the gas being studied was placed in an iron house with walls ten cm thick. The residual ionization was determined by using the method of Hess. By plotting the ionization in the several chambers as ordinate and the ratio of wall area to volume as abscissa, and extrapolating for infinite volume, the amount of cosmic radiation without any secondary radiation from the walls was obtained.

Experimental procedure—An ionization study of several gases was made, using four cylindrical brass chambers which were of different sizes but geometrically similar [*Hess*, 1946], shielded by ten cm of iron and arranged for a null method of measurement employing the Gish-Sherman ionization apparatus with a Lindemann fiber electrometer. The apparatus and procedure used have been described by *Hess* and *Vancour* [1949]. Each of the chambers after careful evacuation was filled in turn with the varicus gases being studied. A linear relation between ionization and pressure (to a very low pressure) was established by measurements at progressive stages of evacuation.

Thanks to the iron shield, there can be no ionization ot the gas in the chamber by radioactive substances of the soil or by decay products of radon, thoron, and actinon in the atmosphere. Accordingly, the observed ionization (in ion pairs per cm³-sec) may be represented by

$$q = q_0 + q_c \qquad (1)$$

where q_0 denotes residual ionization, attributed to alpha particles from the walls of the chamber, and q_c the ionization due to cosmic radiation. The saturation current (esu) is then given by

$$i = eW(q_0 + q_c)$$
$$= eAkn_\alpha + eWq_c \qquad (2)$$

where e is the charge on the electron, taken as 4.803×10^{-10} esu (or 1.602×10^{-19} coulomb); k is the average total number of ions produced by each alpha particle; n_α is the rate of emission of alpha particles per second for each cm² of wall surface; and A and W are the wall area and volume, respectively, of the chamber. Since the height of each cylinder is four times the radius r, we may replace A with $10\pi r^2$ and W with $4\pi r^3$, and (2) may be written

$$i/10\pi er^2 = kn_\alpha + 0.4rq_c \qquad (3)$$

Data bearing on the residual ionization, obtained by again using method I of the 1949 account, are shown in Figure 1. By extrapolating to zero r, we obtain values of kn_α. Taking k as 1.5×10^5 and dividing by k, then multiplying by 3600, we obtain the values of residual ionization shown in Table 1. These are slightly lower than those reported by *Bearden* [1933]; he found values of 0.05 for commercial brass and 0.03 for steel.

'Nozzle' effect—All initial readings at normal pressure (1013 mb or 76 cm Hg) were repeated until there was no appreciable variation in successive readings. This is mentioned because it was found that with some gases, notably CO_2, the ionization immediately after filling was extremely great. Two minutes after filling with CO_2, this ionization amounted to more than 200 ion pairs per cm²-sec. This 'nozzle' effect was also encountered to some extent with hydrogen, but it was much less noticeable with the other gases studied.

For CO_2, it was found upon further investigation that the 'nozzle' effect could be reduced by filling the chambers more slowly. It was possible to eliminate the effect almost entirely by allowing the gas to pass through a filter of calcium chloride. It seems reasonable to assume that this effect was due to large ions, which upon entering the ionization chamber were only very slowly removed by the electric field and by recombination. Figure 2 illustrates the rate of disappearance of this effect. The approximate filling time was 2.5 minutes using a small cotton filter. Readings over a period of two minutes were taken at the indicated intervals after filling with air.

Ionization from cosmic rays—The total ionization produced at normal pressure was plotted (Fig. 3) as a function of the ratio of area to volume. By extrapolating to infinite volume, one may obtain a value for q_c, the ionization produced in each gas by cosmic radiation without secondaries from the

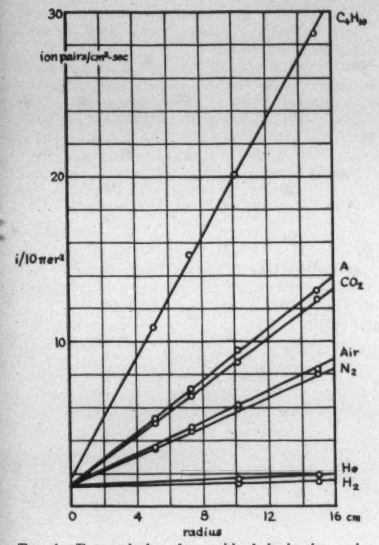

FIG. 1 – Extrapolation for residual ionization using measurements with four chambers

TABLE 1 – *Residual ionization*

Gas	Alpha particles per cm³ hr
Air	0.029
Hydrogen	0.031
Helium	0.033
Nitrogen	0.028
Argon	0.030
Butane	0.040
MEAN	0.032

walls. Values so obtained from Figure 3 are marked "Extrapolated" in Table 2. The 'calculated' values were obtained by subtracting the residual ionization (Table 1) from the observed values. It is obvious that the calculated and extrapolated values are in good agreement. This seems to bear out the essential correctness of our assumption that the residual ionization is due to alpha particles. It must be kept in mind that these values for q_c represent the ionization by cosmic rays at sea level, geomagnetic latitude 51° N, after penetrating four ceilings and floors of our building and ten cm of iron.

Although we are not in a position to compute

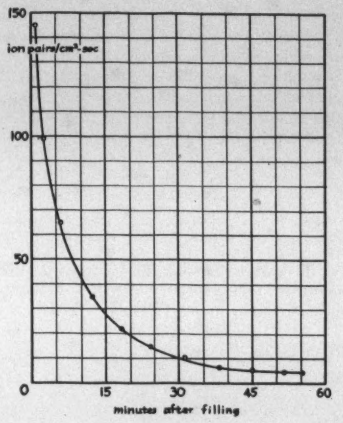

FIG. 2 – Filling effect

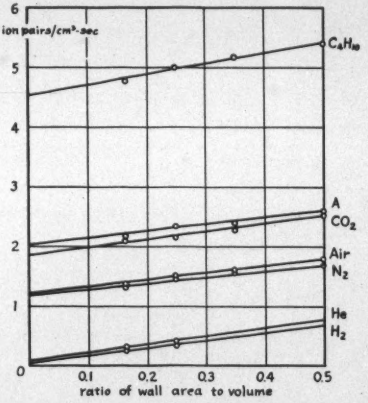

FIG. 3 – Determination of q_c by extrapolation

TABLE 2 – *Values of* q_c

Gas	Calculated	Extrapolated	Mean, relative to air
Air	1.20	1.18	...
H_2	0.04	0.04	0.03
He	0.08	0.09	0.07
N_2	1.18	1.16	0.98
A	1.98	2.02	1.68
C_4H_{10}	4.57	4.53	3.82
CO_2	1.85	1.87	1.56

the specific ionization directly from our experimental results, we can indicate relative values for the specific ionization assuming unity value for air. The resulting values (Table 2, last column) are in accord with those reported by *Clay* [1939] (1.00 for nitrogen and 1.65 for argon) and with that reported by *Hopfield* [1933] for the ratio between argon and nitrogen.

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Frequency of Point and Areal Mean Rainfall Rates

F. A. Huff and J. C. Neill

Abstract—Use of special recording raingages enabled recording of one-minute rainfall amounts from a 50-gage network on a 100-sq mi area in central Illinois during the 1952–53 thunderstorm seasons. One-minute amounts from 19 storms during this period have been used to study the frequency of rainfall rates in shower-type storms under warm season conditions, on both a point-rainfall and areal-mean-rainfall basis. Within the 100-sq mi area, smaller areas of 10, 25, and 50 sq mi were used to obtain an indication of the effect of changing area on the distribution of areal mean rates. The expected tendency for the mean rate to decrease with increasing area was found. For example, the median rate for all 19 storms combined ranged from 1.45 inches per hour for point rainfall to 0.96 inch per hour for the 25-sq mi area to 0.66 inch per hour for the 100-sq mi basin.

The degree to which averaging suppresses details of high rates, as well as the general effects of the averaging process on the distribution curve, was also studied by comparing the distribution of point rates when the rates were based on 1-, 5-, 10-, 15- and 30-minute averages. Results showed the maximum observed rate ranging from 13.80 inches per hour for one-minute to 2.45 inches per hour when based on a 30-minute average. Similarly, when all 19 storms were combined, the median rate ranged from 1.45 inches per hour for one-minute averages to 0.56 inch per hour for 30-minute averages.

Introduction—During 1952–53, one-minute rainfall totals for a number of storms were tabulated in conjunction with a project concerned with the investigation of the utility of radar for quantitative rainfall measurements [*Neill*, 1953]. Use of special recording raingages with 12.6-inch diameter orifices and six-hour charts enabled recording of one-minute amounts from the raingages. Information on the occurrence of rainfall rates within storms should be of interest to hydrologists, especially to those interested in sedimentation and in the design of reservoirs and small drainage systems such as urban storm sewers. Such information is also valuable in evaluating radar for quantitative precipitation measurements and other meteorological uses, since precipitation attenuation is proportional to the rainfall rates within a storm, and attenuation presents an outstanding problem in applying radar to the measurement of rainfall intensity [*Huff* and others, 1956]. Consequently, an analysis was made of the frequency of occurrence of point and areal mean rainfall rates. The available data were restricted to shower-type rainfall occuring during the thunderstorm season from late spring to early fall.

Data used in analysis—One-minute rainfall amounts from 19 storms during 1952–53, tabulated in conjunction with the radar-rainfall project mentioned previously, were used in the study. The one-minute amounts were obtained from 50 recording gages located on a 100-sq mi area encompassing the Goose Creek Watershed in east central Illinois. (Operation of the network and data reduction were partly sponsored by the Signal Corps Engineering Laboratories, Belmar, New Jersey under contract DA-36-039 SC-42446.) The distribution of gages on the network was approximately uniform, the uniformity being limited only by existing road systems and suitable exposures. The network terrain is relatively flat with no distinct topographic features to influence storm behavior.

Careful attention was given to synchronizing the gages so that one-minute rainfall patterns and areal means could be reliably represented. All clocks were checked for accurate timing before installation each spring. Before proceeding to the network to change charts, observer's watches were synchronized with a master clock, which was checked daily with time signals from radio station WWV, the National Bureau of Standards station at Washington, D. C. When installing and removing charts from the drum, the observer made a vertical time check mark with the pen on the chart and entered the exact 'on' or 'off' time from his watch. Charts were changed after each storm and twice a week during periods of no rain to keep any clock-timing errors small. When a raingage record indicated the gage clock had gained or lost a small amount of time, the error was prorated over the period of record. As a further check, after isohyetal maps were plotted for each minute of a storm, gage charts were re-examined if doubtful values appeared at any stations on a one-minute map.

Frequency of point-rainfall rates—The frequency of occurrence of point-rainfall rates in each storm was calculated first, using the data from all 50

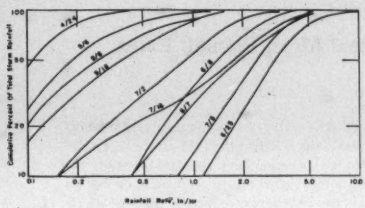

FIG. 1 – Distribution of point rainfall rates in individual storms

TABLE 1 – *Frequency of rainfall rates calculated from various periods (in minutes)*

Cumulative per cent	Rainfall rate (in/hr) equaled or exceeded for				
	1	5	10	15	30
Max.	13.80	7.50	5.72	4.20	2.45
5	5.35	4.10	3.25	2.64	1.62
10	4.20	3.35	2.80	2.34	1.41
20	3.25	2.58	2.13	1.93	1.15
30	2.45	2.02	1.75	1.42	0.88
40	1.90	1.52	1.34	1.07	0.69
50	1.45	1.16	0.97	0.82	0.56
60	1.05	0.83	0.70	0.62	0.44
70	0.68	0.54	0.46	0.41	0.33
80	0.37	0.28	0.25	0.23	0.21
90	0.15	0.12	0.11	0.11	0.10
95	0.08	0.07	0.07	0.07	0.06

TABLE 2 – *Per cent of one-minute rate for various periods (in minutes)*

Cumulative per cent	Per cent of one-minute rate for			
	5	10	15	30
Max.	54	41	30	18
5	77	61	49	30
10	80	67	56	34
20	79	66	59	35
30	82	71	58	36
40	80	71	56	36
50	80	67	57	39
60	79	67	59	42
70	79	68	60	48
80	76	68	62	57
90	80	73	73	67
95	87	87	87	75

gages. Figure 1 shows cumulative frequency curves for the 1953 storms. The graph shows cumulative percentages plotted against rainfall rate in inches per hour, based upon one-minute amounts from all 50 gages. For example, in the storm for July 2, 50 pct of the rainfall occurred at rates exceeding 0.90 inch per hour, while for the storm of June 25, 50 pct of the total rainfall occurred at rates exceeding 3.10 inches per hour.

Examination of the 19 storms indicated that the group should be approximately representative of conditions experienced during the warm season in the Midwest. Consequently, the data were combined to determine the frequency of point rainfall rates under average conditions during a season. Results of this analysis are shown in Table 1. It will be noted that on the average (based on one-minute rates in the 19-storm sample) 50 pct of the warm season rainfall occurs at rates exceeding 1.45 inches per hour. However, the median rate in individual storms in the 19-storm sample was highly variable, ranging from 0.10 to 3.10 inches per hour.

For comparison purposes, the per cent of total storm rainfall occurring at various rainfall rates

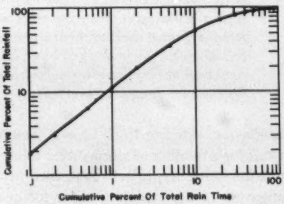

FIG. 2 – Time distribution of point rainfall

TABLE 3 – *Frequency of areal rainfall rates*

Cumulative per cent of rainfall	Rainfall rate (in/hr) equaled or exceeded for given area (sq. mi)					Per cent of point rate			
	Point	10	25	50	100	10	25	50	100
Max.	13.80	4.08	4.02	3.18	2.88	30	29	23	21
5	5.35	3.48	2.82	2.52	2.40	65	53	46	45
10	4.20	3.18	2.55	2.22	1.86	76	61	53	44
20	3.25	2.28	2.22	1.74	1.35	70	68	54	42
30	2.45	1.80	1.77	1.32	1.11	73	72	54	45
40	1.90	1.26	1.26	1.02	0.90	66	66	54	47
50	1.45	1.02	0.96	0.78	0.66	70	66	54	46
60	1.05	0.72	0.72	0.54	0.48	69	69	51	46
70	0.68	0.48	0.48	0.36	0.28	71	71	53	41
80	0.37	0.25	0.26	0.18	0.16	68	70	49	43
90	0.15	0.11	0.12	0.10	0.08	73	80	67	53
95	0.08	0.07	0.07	0.05	0.04	87	87	62	50

TABLE 4 – *Time distribution of areal rainfall rates*

Area	Per cent of total rain time accounting for given per cent of total rainfall				
	10	25	50	75	90
sq.mi.					
Point	1	3	10	25	48
10	1	3	11	26	51
25	1	4	11	27	53
50	1	4	12	28	55
100	1	4	12	30	58

was determined when these rates are based on 5-, 10-, 15-, and 30-minute summation periods (Table 2). Obviously, as the time factor is increased in calculating rainfall rates in a storm, the averaging process suppresses details of the high rates occurring during the averaging period. Most studies in the past, such as those of *Yarnell* [1935] and the *U. S. Weather Bureau* [1955], on which engineering design has been based have been calculated on the basis of periods from five minutes upward. Hydrologists have found that rainfall rates for periods less than 10 to 15 minutes rarely have practical significance with respect to runoff from a drainage area. However, shorter-period rates, especially one-minute values which closely approximate actual conditions within storms, are pertinent to the understanding of the physical structure of storms. Furthermore, these short-period rates have practical application, such as in the evaluation of radar for meteorological purposes, as mentioned previously. In the present study, an attempt was made to ascertain the effect of the averaging process on the observed frequency of rainfall rates.

Referring to Table 1 it is seen that when one-minute totals are used, 50 pct of the rain was found to occur at rates exceeding 1.45 inches per hour. When a five-minute base period was used, the 50 pct value dropped to 1.16 inches per hour and then to 0.97 inch per hour for a ten-minute base period, 0.82 inch per hour for a 15-minute period and 0.56 inch per hour for a 30-minute period. Also, note in Table 1 the rapid decrease in the maximum observed rainfall rate when this rate is based on various averaging periods. The averaging effect is further illustrated in Table 2, where the longer period values have been expressed as percentages of the one-minute values.

The time distribution of point rainfall was studied next, combining data from all 19 storms. Results of this analysis are shown in Figure 2 where per cent of total rain time has been plotted against per cent of total rainfall. From this curve it is seen that ten per cent of the season rainfall (based on the 19-storm sample) occurs in approximately one per cent of the time it is raining, 50 pct of the rain occurs during about ten per cent of the time that rain is falling, and 90 pct of the total rain occurs in 50 pct of the time that it is raining. Thus, it is apparent that warm season rainfall tends to occur in strong bursts within a storm period; that is, most of the rain tends to occur in a small portion of the storm.

Frequency of areal mean rainfall rates—The foregoing discussion has been concerned with the frequency of point rainfall rates. Frequently, hydrologists and meteorologists are more concerned with areal than with point relationships. Consequently, data for the 19 storms from the 50-gage network on the 100-sq mi watershed were further analyzed to obtain areal frequency relationships. For this purpose, the 100-sq mi network was further subdivided to give areas of 10, 25, and 50 sq mi for comparison with the 100-sq mi network relationships. One-minute areal mean rates were calculated for each minute in each storm for each of the areas mentioned above.

All 19 storms were then combined to obtain average relationships for the various areas. Reference to Table 3 shows the expected trend. For example, 50 pct of the point rainfall was found to occur at a rate exceeding 1.45 inches per hour, while 50 pct of the areal mean rainfall occurred at rates of 1.02, 0.96, 0.78 and 0.66 inches per hour, respectively, for the 10-, 25-, 50-, and 100 sq mi areas. Table 4 illustrates the variation in the time distribution of rainfall rates as the area is increased. For example, 50 pct of the point rainfall was found to occur during ten per cent of the time it is raining. At 25 sq mi, 50 pct of the areal mean rainfall occurs in 11 pct of the time, while for 100 sq mi, 50 pct occurs in 12 pct of the time. This table shows a tendency for the time distribution to change only very slowly with increasing area.

Evaluation of results—Although the results in this study are based upon a relatively small sample, the variety of storms incorporated in the 19-storm sample should make the results approximately representative of the average warm season conditions in the Midwest. It is hoped that the results will prove useful in evaluating the distribution of rainfall rates in warm season rainfall.

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Large-Volume Water Samplers*

W. G. Van Dorn

Abstract—Two new sea-water samplers have been developed to collect water in larger volumes (one and 12 gal) than the conventional Nansen bottle. Both are constructed of plastic which is relatively inert chemically, are free-flushing, and can be either messenger- or bottom-actuated.

The one-gallon sampler—The one-gallon (four-liter) sampler is simply a clear 4.5-inch diameter plastic (Plexiglas) tube, 15 inches long, clamped to the hydrographic wire by a wing nut (Fig. 1). The tube is sealed at both ends by 'plumber's friends,' known to the trade as 'force cups,' held in place by an appropriate length of heavy elastic surgical tubing. The rubber tubing is secured to the force cup by a $\frac{1}{4}$-28 NF brass machine screw, whose head is inserted about $\frac{1}{2}$ inch into the tubing and held by a ligature of nylon thread. An 11/16-inch diameter brass washer is slipped over the bolt, which then passes through a hole made in the rubber diaphragm of the force cup and is held on the other side by a nut over a $1\frac{1}{4}$-inch diameter micarta washer. Tightening the nut upsets the rubber tubing to form a tight, non-metallic seal.

In the cocked (pre-tripped) position (Fig. 2), the cups are drawn around to the sides of the tube by stretching the elastic, and they are held there by short loops of stainless steel wire cable slipped over a trigger pin. During descent the open-ended tube offers virtually no restriction to the flow of water through it. When tripped by a messenger, the cups (and auxiliary messenger, as desired) are released and snap snugly into the ends of the tube to make a tight seal. After removal from the wire, the sampler can be hung from a rack and left as long as desired without fear of leakage, even with vigorous shaking.

Draining and venting are effected through short latex hoses equipped with pinchcocks, although plastic plugs or petcocks could as easily be installed. The transparent plastic body permits visual inspection of the contents and the liquid level remaining after partial emptying.

Since Plexiglas is a fairly poor conductor of heat, a thermometer within the tube will read within a degree or two of the *in situ* temperature of the sample if it reaches the surface without unusual delay. The capacity of this sampler can be increased simply by increasing the length of the tube, but at lengths of more than three feet (about three gallons) the internal hydrostatic pressure after venting is sufficient to break the lower seal and cause leakage when the sampler is out of water.

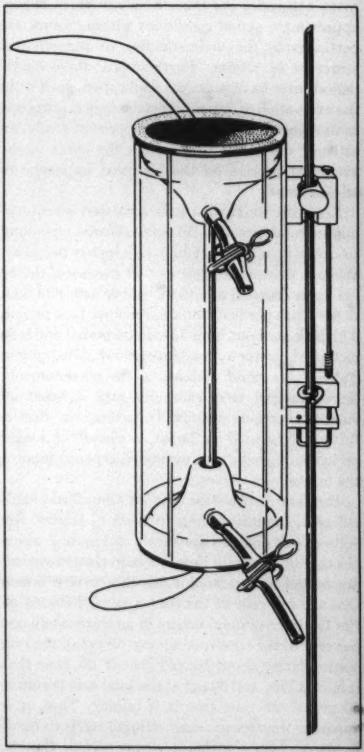

Fig. 1 – One-gallon water sampler, closed; the hydrographic wire first passes through the split ring on the lower support and then lies in a groove in the upper support and in a matching groove in the head of a bolt passing through this support; it is clamped firmly by tightening a wing-nut on the other end of the bolt

* Contribution from the Scripps Institution of Oceanography, New Series, No. 834.

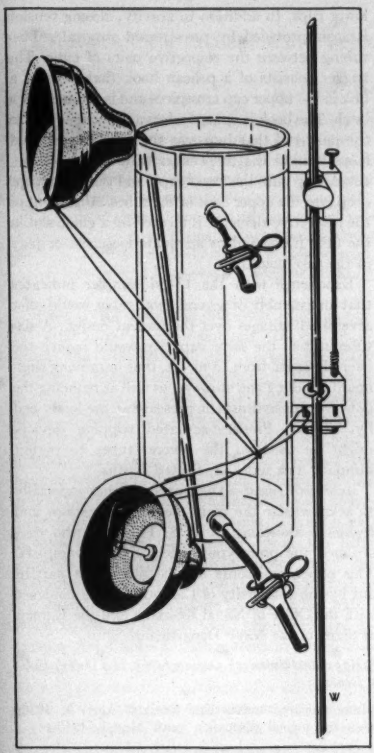

FIG. 2. – One-gallon water sampler in pre-tripped position; impact of the messenger on the upper end of the spring-loaded J-shaped trigger rod releases the stainless steel wire loops held by the short arm of the trigger rod in a V-shaped groove in the lower support

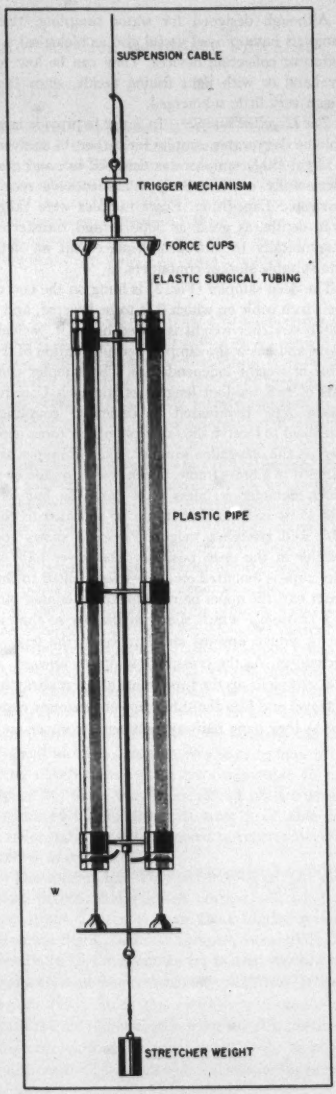

FIG. 3

FIG. 3 – Twelve-gallon water sampler in cocked position; a link joined by an eye to the crosspiece holding the upper force cups passes over a pelican hook on the ¾-inch bar; the end of the pelican hook in turn is restrained by the left arm of the horizontal link of the trigger mechanism; when the messenger strikes the push rod looped around the suspension cable above the swivel, the right arm of the link is pushed downward, freeing the pelican hook, which in turn frees the link; the rod supporting the tube frame is not shown

Although designed for water sampling, these samplers have proved useful also as biological and sediment collecting devices. They can be lowered by hand or with light fishing tackle, since they weigh very little submerged.

The 12-gallon sampler—In order to provide large volume deep-water samples for carbon-14 analysis, a 12-gal (50-l) sampler was designed for, and used successfully on, the Scripps Institution's recent Eastropic Expedition. Eight samples were taken from depths as great as 3000 m and transferred anaerobically by nitrogen displacement on deck into suitable storage containers.

The deep sampler (Fig. 3) is hung on the end of the winch cable on which it is to be lowered, and a 100-lb stretcher weight is added below it. Swivels above and below the sampler permit rotation of the cable or weight independently. The sampler consists of two ten-foot lengths of five-inch Uscolite plastic pipe terminated in cemented couplings machined to receive the same plumber's force cups used on the one-gallon sampler. The twin pipes are clamped to a brass frame, which is free to slide on a $\frac{3}{4}$-inch diameter stainless steel bar. The bar has eyes at its ends so that it can be shackled to the cable and stretcher weight. Figure 3 shows the sampler in the open position. The lower pair of force cups is mounted on a crosspiece bolted to the center bar; the upper pair is similarly mounted but on a crosspiece which slides on the bar so that it can be drawn upward and latched to the trigger mechanism. As the crosspiece is drawn upward, a short rod picks up the tube frame about midway in its travel and lifts the tubes free of the lower cups so that they hang halfway between the upper and lower cups. In addition to gravity, closing tension is again provided by pre-stressed surgical rubber tubing between the respective pairs of cups. The trigger consists of a pelican hook that engages a link in the upper cup crosspiece and is retained by a latch. The hook is opened when a messenger strikes the push rod that bypasses the upper swivel and loops around the suspension wire. Upon release, tubes drop onto the lower cups, and the upper cups drop into the upper ends of the tubes. Alignment of the respective elements is insured by a guide slot in the tube frame and by adequate looseness or play in the cup mountings.

Experience with the 12-gal sampler indicates that an assembly of several short tubes would offer several advantages over the present design. A six-tube unit of the same capacity would reduce the over-all length from 15 to 9 ft, thus improving shipboard handling and stowage, as well as reducing the out-of-water hydrostatic pressure at the lower end by 70 pct. Pressure-actuated tripping devices might be used on the several tubes to permit sampling at a series of selected depths.

Acknowledgment—The author wishes especially to acknowledge the many helpful suggestions and technical assistance of C. S. Fleming, who constructed the prototype models of both samplers. This paper represents results of research carried out by the University of California under contract with the Office of Naval Research and the Bureau of Ships of the Navy Department.

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Evidence for a Critical Wind Velocity for Air-Sea Boundary Processes

HUGO MANDELBAUM

Abstract—Five thousand simultaneous wind and current observations at Amrum Bank Lightship are analyzed to contribute toward the solution of the controversial question of the existence of a critical wind speed for air-sea boundary processes. The observations are grouped according to eight wind forces (Beaufort scale) and subjected to harmonic analysis. The residual current is further analyzed to yield a current that can be considered as exclusively wind-driven. Upon plotting these current velocities W against wind velocities V in cm/sec, the graph shows a definite discontinuity between the wind velocity Groups 1 to 4 and 5 to 8. There is a marked reduction in current speed between wind forces 4 and 5 and a lower ratio of increase of W against V for higher wind velocities.

Munk [1947] concluded that there exists a critical wind speed at approximately 660 cm/sec at which the processes at the air-sea boundary undergo a pronounced discontinuity. White caps in greater number appear at the crests of wavelets at winds above the critical speed. The smooth appearance of the waves changes into roughness, indicating a change from laminar flow at the boundary to turbulence. Munk interpreted the appearance of a critical wind velocity as a consequence of the instability criterion of Kelvin and Helmholtz. Below the critical speed the little wavelets which appear superimposed upon the characteristic wind waves are stable, that is, they are smoothed by the surface tension of the water, while above the critical speed the roughness increases and causes a change-over of the sea-air boundary from a laminar to a turbulent state. As evidence for the existence of a critical wind speed Munk compared observed current velocities with simultaneous wind velocities and calculated a coefficient of friction for the air-water boundary which showed a discontinuity between winds of lower and of higher velocities.

Neumann [1951] argued against the existence of such a critical wind speed on the basis that the observational values used by Munk for the calculation of the frictional coefficient are not comparable with each other and that a discontinuity based on such material is rather hypothetical.

Roll [1952] critically discussed the arguments of both sides and concluded that there may exist a critical wind speed which, however, depends on the length of the fetch of the wind-generated waves. In coastal waters the character of the water surfaces seems to change in the neighborhood of 7 m/sec wind velocity, while in the open ocean it can be expected that turbulence occurs already below such wind speeds.

In a later paper *Roll* [1954] also calculated a coefficient of friction which shows an increase with rising wind speed and no discontinuity. The calculations are based on the difference between the wind velocity at the water surface and that at 19 m above by taking into consideration the influence of the temperature profile within this air column.

His results, however, are not conclusive, since the calculations were based only on winds up to 4.5 of the Beaufort scale. An extrapolation of functions below that speed to situations above that speed necessarily will obscure any discontinuity which actually may exist within the wind-speed interval above 4.5 in the Beaufort scale.

In the following an attempt is made to correlate the velocity of the wind-driven water current to the velocity of the wind in order to obtain information whether a discontinuity exists in this relationship. Two problems confront us in such an investigation: (1) Current velocities are not only a function of wind velocity but also considerably depend on wind direction. We have to find, therefore, observations which are comparable to each other. (2) Since wind velocities at sea are usually estimated by the Beaufort scale a suitable conversion table must be selected to express Beaufort values in cm/sec.

The author has very recently analysed more than 20,000 simultaneous current and wind observations made at Amrum Bank Lightship in the German Bight [*Deutsche Seewarte*, 1924–1933]. The results of this analysis as far as the residual currents are concerned are already published [*Mandelbaum*, 1955]. Since this analysis was carried out with the aid of punched cards a suitable portion of the observational material could easily be picked out from the total of all observations for the present analysis.

The following considerations guided this selec-

TABLE 1 – *Wind-generated currents at Amrum-Bank Lightship*

Wind direction	Wind force (Beaufort)			Wind force (Beaufort)			Number of observations
	1 & 2	3 & 4	5 +	1 & 2	3 & 4	5 +	
	Current velocity			Current direction			
	cm/sec	cm/sec	cm/sec	°	°	°	
E	4.4	5.7	6.8	280	269	262	1345
ESE	4.4	5.7	6.7	310	303	299	1089
SE	4.5	6.0	6.7	333	332	333	1320
SSE	4.6	6.8	8.2	353	351	358	919
S	4.8	7.3	9.4	9	7	13	1128
SSW	4.6	7.3	10.0	26	21	28	1339
SW	4.1	6.6	9.5	44	37	42	2030
WSW	3.5	5.6	8.2	68	59	59	1527
W	3.2	4.8	6.7	100	89	82	1807
WNW	3.5	4.8	5.8	130	123	119	1421
NW	4.1	5.8	6.6	153	152	153	1954
NNW	4.6	6.8	8.2	173	171	178	1092
N	4.8	7.3	9.4	189	187	193	918
NNE	4.6	7.3	10.0	206	201	208	671
NE	4.5	6.8	9.5	229	217	222	903
NNE	4.4	5.8	8.2	248	239	239	871

TABLE 2 – *Correction factors for the reduction of calculated current velocities to maximum values*

Wind force (Beaufort)	1	2	3	4	5	6	7	8
Correction	1.20	1.16	1.12	1.09	1.06	1.05	1.04	1.02

tion. Since the previous analysis showed that the current velocity for the same wind force varies considerably with the direction of the wind (Table 1), only observations made at winds blowing from the same direction will provide values which are comparable with each other. For the present analysis observation made with SW winds were selected. Winds from this sector are predominant in the German Bight; hence a greater number of current observations is made available by this selection (Table 1, last column). In order to increase the number of observations, those made with SSW and WSW winds were added. Since the numbers of observations in both groups (1339 and 1527) are of the same order, the resultant current of the combined groups can be taken as caused by SW winds.

As can be seen from Table 1, low wind speeds produce maximum current velocity when they blow from S, while for strong winds the direction for maximum current is SSW. Winds from SW at forces 1 and 2 Beaufort produce a current of only 4.1 cm/sec as compared to a maximal current velocity of 4.8 cm/sec from S winds of the same force; that is, the current produced by SW winds is only 85 pct of the maximal current velocity at forces 1 and 2. But for winds of forces 3, 4, and 5 and above the percentages are higher, namely, 90 and 95 pct respectively. In order to make current values measured with SW winds of different force comparable to each other they were reduced to the maximum current velocity at each particular wind speed. Table 2 contains the correction factors which were applied to the current velocities calculated for SW wind of varying force. They were arrived at by interpolation and extrapolation from the above-mentioned percentages.

The analysis of the material was carried out in the following manner. The observations were divided into eight groups according to the wind force, one group for each Beaufort force from 1 to 7, with all observations from 8 and above combined in Group 8. Each group was then subjected to harmonic analysis, and two right-angular components M_n of the current at 24 moon-half-hours of the M_2-tide current were calculated. These are tabulated in Table 3. The non-periodic residual current is then the mean R of these 24 M_n. For Groups 7 and 8 the total number of observations is comparatively small, and for some moon-half-hours no values could be calculated. In order to avoid the necessity of applying weights to each M_n, which makes the analysis very time-consuming, the gaps were filled by interpolated values which were arrived at graphically. In Table 4 the two components of the residual currents are tabulated. In order to arrive at that part of the residual current which is caused by the wind only, a residual current at calms was defined and calculated [*Mandelbaum*, 1955] for winds of forces 1 and 2, 3 and 4, and 5 and more. The residual currents at calms for eight different wind velocities were arrived at by interpolation from the given three values. They are presented in Table 4, columns 5 and 6. These residual currents at calms are subtracted from the total residual current. The difference represents the pure wind-generated current (Table 4, columns 7 and 8). The resultants of these wind-generated currents are tabulated in columns 9 and 10. After multiplying with the correction factors of Table 2 we finally arrive at current velocities for eight different wind forces which are comparable with each other (column 12).

A glance at the values immediately shows a discontinuity between forces 4 and 5 Beaufort. In order to derive the functional relationship between wind and current velocities we are confronted with the problem of how to convert the estimated wind forces expressed by the Beaufort scale into cm/sec. Various attempts have been made to correlate the

TABLE 3 – *Tidal current and residual current at winds blowing from SSW to WSW at various velocities*

Moon half-hour	Wind force (Beaufort)							
	1		2		3		4	
	Current component							
	NW	NE	NW	NE	NW	NE	NW	NE
1	23.04	11.44	27.83	11.63	31.10	13.61	35.80	19.47
2	33.23	8.69	34.49	13.79	37.45	8.76	33.26	13.93
3	43.36	10.36	41.53	13.80	36.22	11.39	38.64	11.46
4	42.06	6.36	40.11	11.84	38.48	10.52	44.57	11.49
5	41.72	5.72	41.41	6.89	42.04	8.59	40.45	5.28
6	42.89	2.68	39.97	6.93	41.59	4.82	39.22	6.06
7	41.27	5.69	35.25	4.67	35.19	1.74	39.40	6.95
8	24.30	0.03	25.52	1.22	31.19	1.36	33.03	2.73
9	25.25	−1.25	24.70	0.82	21.88	3.72	28.80	4.15
10	15.04	−2.50	16.24	−2.09	8.36	2.19	8.19	3.88
11	2.43	−3.30	−4.18	−1.13	3.12	0.39	2.81	3.72
12	−9.38	−2.13	−10.21	2.02	−14.66	2.06	−15.95	1.39
13	−18.65	−1.38	−21.03	0.73	−27.77	3.65	−24.03	4.42
14	−29.69	2.73	−34.30	2.67	−31.60	5.12	−33.43	8.55
15	−31.27	8.86	−34.51	2.42	−35.70	4.59	−28.55	6.89
16	−40.20	5.88	−31.94	3.98	−34.11	5.69	−33.96	11.73
17	−41.26	5.35	−33.95	6.69	−30.55	7.23	−32.69	11.11
18	−32.58	6.21	−31.69	7.78	−27.00	8.93	−20.25	13.91
19	−24.00	8.86	−24.28	9.30	−24.12	10.00	−20.80	13.29
20	−16.18	4.00	−20.70	8.70	−13.47	14.33	−14.32	17.94
21	−9.86	8.31	−4.97	12.34	−7.59	10.98	−10.00	13.09
22	−4.56	9.08	−0.93	9.15	4.90	10.92	1.24	15.69
23	9.79	12.79	10.45	13.23	13.24	12.49	12.35	19.30
24	22.30	9.52	21.04	14.35	20.84	12.20	23.40	16.89
R	4.61	5.08	4.41	6.74	4.96	7.30	6.13	10.14
	5		6		7		8	
1	38.48	15.68	28.43	14.57	23.00	15.86	28.33	9.33
2	38.41	12.48	33.00	12.88	30.00	12.67	19.75	4.00
3	37.84	10.06	40.00	12.57	36.00	15.83	34.14	8.86
4	37.58	7.37	38.23	7.69	44.20	4.80	43.80	11.20
5	40.13	2.67	44.14	2.00	52.00	7.20	49.80	12.40
6	40.87	4.87	40.41	6.68	33.00	11.57	35.25	10.50
7	34.61	3.08	35.15	7.08	38.17	7.00	39.00	10.67
8	32.71	2.06	34.45	4.18	35.44	0.00	38.50	1.50
9	24.33	1.56	19.38	0.00	18.00	9.40	1.25	0.75
10	15.63	2.75	12.29	3.35	17.83	11.67	4.00	3.33
11	−7.54	6.35	−2.79	4.86	−3.25	5.50	−10.00[a]	5.00
12	−8.81	6.69	−14.09	5.91	−22.40	18.40	−24.33	25.33
13	−22.08	4.85	−20.00	1.33	−20.00[a]	10.00	−27.00[a]	15.00
14	−22.67	11.47	−23.63	12.75	−23.25	12.38	−32.33	29.67
15	−36.12	6.76	−29.41	17.91	−26.60	8.20	−47.00	20.00
16	−33.19	3.57	−29.47	13.13	−23.50	3.00	−37.40	3.20
17	−31.46	11.71	−28.55	12.65	−26.20	15.20	−32.83	17.50
18	−31.00	12.81	−26.00	20.90	−25.63	8.13	−20.50	23.50
19	−22.60	15.52	−15.15	14.00	−20.22	18.22	−9.25	35.75
20	−16.84	6.05	−19.53	15.87	−19.00	11.25	−14.83	22.00
21	−6.88	15.06	−10.00	16.86	−17.75	15.50	−11.00	13.75
22	5.21	16.58	6.00	9.00	4.33	5.17	14.00	33.00
23	14.21	19.18	8.86	17.93	16.25	17.00	17.00[a]	17.00
24	30.79	15.32	20.36	9.18	12.00	17.00	24.17	9.67
R	6.11	8.94	5.92	10.14	5.52	10.87	3.44	14.29

[a] Interpolated values

TABLE 4 – *Computed wind current at various wind velocities*

Wind force (Beaufort)	No. of observ.	Residual current		Residual current at calms		Wind current		Resultant wind current		Corr. factor	Maximum resultant
		NW	NE	NW	NE	NW	NE	r	θ		
1	2	3	4	5	6	7	8	9	10	11	12
1	568	4.61	5.08	4.90	1.95	−0.29	3.13	3.15	50° 20′	1.20	3.80
2	1164	4.41	6.74	4.70	1.90	−0.29	4.84	4.83	48° 20′	1.16	5.61
3	1277	4.96	7.30	4.50	1.90	0.46	5.40	5.40	41° 10′	1.12	6.07
4	854	6.13	10.14	4.30	1.80	1.83	8.34	8.49	32° 10′	1.09	9.22
5	520	6.11	8.94	4.15	1.50	1.96	7.44	7.69	30° 10′	1.06	8.18
6	288	5.92	10.14	4.00	1.30	1.92	8.84	9.05	32° 30′	1.05	9.52
7	140	5.52	10.87	3.90	1.20	1.62	9.67	9.80	35° 20′	1.04	10.21
8+	85	3.44	14.29	3.70	1.10	−0.26	13.19	13.19	45° 00′	1.02	13.59
Total....	4896										

estimated Beaufort scale with measured wind velocities. The International Sea Scale (1946) proved to be not quite adequate. The Germans use a conversion table based on calculations by *Seilkopf* [1939]. I am grateful to H. U. Roll who informed me of the results of an unpublished investigation by Richter. This table is based on the study of 10,000 simultaneous observations from German lightships. It deviates not inconsiderably from the previously used sea scale. I am informed also by Roll of an attempt made by G. Verploegh of the Netherlands Meteorological Institute. The results, also unpublished, were taken from Figure 5 in *Roll* [1954].

Moreover, since an estimation of the wind force at sea by the Beaufort scale is based on the state of the water surface, it is an expression of the wind velocity near the water, while measurements of wind velocity are made at the masthead 60 to 90 ft above the water surface. The wind velocity near the surface cannot be expected to be proportional to the measured velocity at the masthead. This ratio depends on the temperature profile in the lower layers of the air [*Roll*, 1954]. In stable conditions, that is, colder air near the water, the ratio is smaller than in unstable conditions. When the wind force was estimated at Beaufort 2, the wind velocity at the masthead was measured as 4.3 m/sec in stable conditions and as 3.1 m/sec in unstable conditions. It stands to reason that the wind velocity will also affect the ratio of surface wind velocity to wind velocity at the masthead. Turbulence at higher wind speeds might affect this ratio in the same sense as an unstable temperature profile.

Roll [1954] has experimentally derived a formula which correlates measured wind velocities near the water surface (at 0.5 m height) to the Beaufort scale; however, his observations were made at wind forces not higher than Beaufort 4.5, and it is very doubtful whether we are entitled to extrapolate this formula beyond the limit of the observational material. At higher wind forces another ratio might be encountered. As will be shown, this is not only a possibility but a very high probability. As mentioned previously, Roll calculates a coefficient of friction on the basis of a uniform linear relationship between Beaufort values and measured wind velocity at 0.5 m height for all wind speeds, and naturally he finds no discontinuity anywhere. But if there is discontinuity in the ratio of Beaufort to the measured wind velocity, the coefficient of friction will also prove to be discontinuous.

In order to determine the relationship between the wind speed and the current velocity, the current velocities calculated for the various Beaufort forces (Table 4, last column) were plotted (see Fig. 1) against the wind velocities, converted into m/sec by four different scales—those of Roll, Verploegh, Richter, and Seilkopf. The last three represent wind velocities measured at about 60 ft above the water surface, the first one wind velocities measured at 0.5 m above the water surface. The discontinuity in the graphs (Fig. 1) between the wind forces 4 and 5 appears at a wind speed of about 6 m/sec near the surface, or about 9 m/sec at 20 m height. If we assume a linear relationship between the current velocity V and the wind velocity W of the form $V = kV + c$ and if k_1 is the proportionality factor at lower wind speeds and k_2 that at stronger winds, then the graphs show that in all scales $k_2 < k_1$. From this fact we may well conclude that an extrapolation of Roll's linear function $V_{0.5} = \frac{1}{3}B$ (m/sec) beyond the value of 4.5 of the Beaufort scale, for which it was calculated, is not justified. If we are right in assuming, as *Munk*

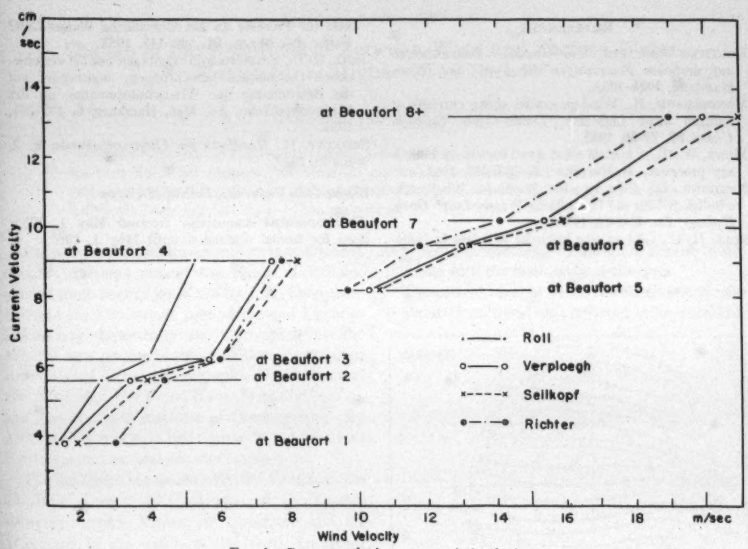

FIG. 1 – Current velocity versus wind velocity

[1947] did, that the discontinuity between wind force 4 and 5 is caused by a change from laminar flow to turbulent flow at the air-water boundary, we may also explain the decrease of the proportionality factor ($k_2 < k_1$) at higher wind speed as caused by loss of energy in the air due to turbulence. In turbulent air, however, the drop in wind speed from 20 m height to that near the water surface might not be as great as at a laminar flow pattern at lower wind speeds. This would mean that the ratio k_2/k_1 for the Roll scale would even be smaller than it is for the other scales.

In order to determine how reliable these results are, the mean error of the calculated values for the wind-driven current (Table 4, column 12) must be known. Since the mean error cannot be found without calculating all harmonic constants and the time-consuming complete synthesis of the Fourier function, an attempt is made to estimate the error of the calculated values. In general the error decreases with the increase in the number of the original observations. It depends also on the principle of selection of these observations from the total of all observations that were made at a regular time schedule. *Mandelbaum* [1955] in his study of wind-driven currents at Borkum Riff found that by a selection similar to the present, and with the number of observations ranging from 500 to 1000, the mean error of the R_n ranged between 0.6 and 0.9 cm/sec. For 200 observations the error is about 1.5 cm/sec. The drop between wind forces 4 and 5 might well be due to the uncertainty of our calculated values. However the decrease in the constant k from lower speed to higher speed is based on a difference greater than this error. Moreover the values for wind forces 5 to 8 are very regularly arranged, as the small mean deviation (Table 5) indicates. We may therefore assume that the change in k at least is real. The small increase in current velocity from forces 4 to 7 indicates also that the discontinuity between forces 4 and 5 is most probably real.

TABLE 5 – *Functional relationship of current velocity V (cm/sec) and wind velocity W (m/sec) for different conversion scales (Beaufort to m/sec), $V = kW + c$*

Conversion Scale	Wind force 1 to 4			Wind force 4 to 8			Ratio k_2/k_1
	k_1	c_1	V	k_2	c_2	V	
Roll	1.26	2.0	0.57				
Verploegh	0.84	2.4	0.63	0.52	2.6	0.21	0.62
Seilkopf	0.79	2.2	0.50	0.48	3.0	0.26	0.61
Richter	1.05	0.6	0.49	0.54	3.1	0.26	0.51

V = mean deviation of calculated value from functional value.

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Change in the Relationship Between Wind and Surface Water Movement at Higher Wind Speeds*

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Abstract—Analysis of continuous current measurements aboard four light vessels in the southern North Sea suggests that while the expression connecting wind and surface water movements is linear up to winds of about Beaufort 3, above this strength it appears to obey a different linear relationship or to become curved.

The program of continuous current measurement aboard lightships around the coasts of Britain, started some twenty years ago by J. N. Carruthers (then of the Ministry of Agriculture and Fisheries Laboratory, Lowestoft) was interrupted by the War; it was resumed late in 1950 as a combined commitment of the Hydrographic Department of the Admiralty, the Royal Naval Scientific Service, and the National Institute of Oceanography. By 1953 two years of data had been collected from four lightships and an analysis was commenced.

The lightships concerned were the Varne, in the Straits of Dover; the Galloper, off the Thames estuary; Smith's Knoll, off Lowestoft; and S.2 (German), in the middle of the North Sea about halfway between Flamborough Head and Wilhelmshaven. Their positions thus varied from the open sea to close inshore and in a narrow strait, giving rise to quite a wide range of different water conditions.

It is as well to state now that the findings described later cannot be compared with those arising from a carefully controlled laboratory experiment. In the first place, each observation lasted for a mean tidal or lunar day of 24 hr 50 min, thus containing a tidal element which had to be eliminated by rather rough and ready means. Secondly, the method of operation of the current meters used gave the 'length' of water passing the lightships in a mean tidal day in eight 45° octants, and thus water movements had to be taken as reciprocal which might in fact be up to 45° 'out' of the reciprocal. Thirdly, the observations were taken by the lightship crews—unskilled personnel who might easily make mistakes. Finally, the wind speed and direction were estimated, and the connection between the Beaufort scale of wind strength and wind travel was an arbitrary one. Nevertheless, with over 700 daily observations available from each lightship, it was found necessary to discard only a very small percentage which did not appear to fall into line with the main body of the data.

The current layer to which the observations refer is about 1½ m 'thick' and centered at between four and five meters from the surface. The wind was estimated at deck level, about three or four meters above the sea.

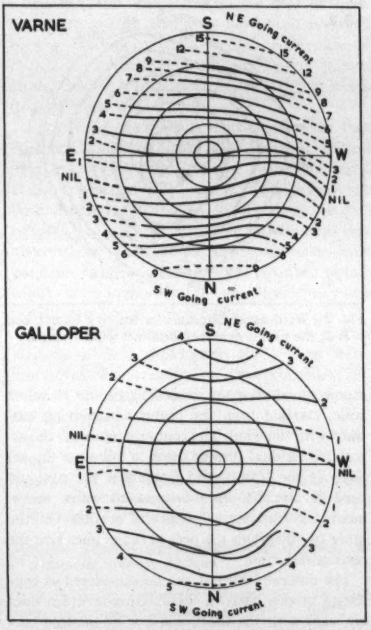

Fig. 1 – Wind-water diagrams for Varne and Galloper; the circles represent Beaufort wind strengths from 1 to 5

Figures 1 and 2 illustrate the connection which was arrived at between wind and water movements at the four lightships. The concentric circles

* Summary of part of National Institute of Oceanography Internal Report no. A. 3, July, 1955.

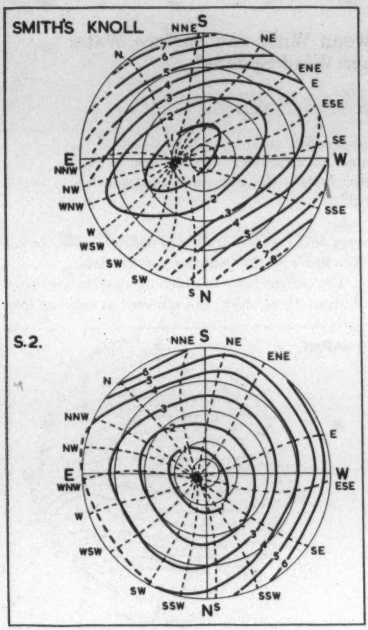

FIG. 2 – Wind-water diagrams for SMITH'S KNOLL and S. 2; the circles represent Beaufort wind strengths from 1 to 5

represent wind speed according to the Beaufort scale, starting from the center and moving outward with the wind. The contours represent the associated residual current speed in miles per (lunar) day. At the VARNE and GALLOPER the contours become 'straight' lines because all water movements recorded lay in reciprocal octants. On the other two diagrams the pecked radial lines give the current direction.

The observed current can be considered as consisting of two parts: a 'basic' current which does not vary with the wind, and a wind-induced current. In the VARNE and GALLOPER diagrams the basic current is given by the amount the 'no current' contour is displaced to one side of the 'no wind' point, and in the other diagrams by the vector from the 'no current' point to the 'no wind' point.

Note that at the VARNE and GALLOPER, where water movements are constrained by the coastal configuration, the tidal streams run apparently reciprocally and give rise to a current whose main directions seem to vary little about the NE-SW line. At SMITH'S KNOLL, where the coast is about 15 mi distant to the WSW, a wind up or down the coast is associated with a greater current than an offshore or onshore wind of the same strength. On the other hand, the contours at S.2, in the open sea, are more nearly circular than at SMITH'S KNOLL, indicating that here winds from all directions have much the same effect.

From Figures 1 and 2 it is possible to plot the current against the wind for any particular wind direction. This has been done for VARNE and GALLOPER in Figure 3. The wind directions selected were those which gave the maximum current/wind percentages.

At low wind strengths the current/wind relationship appears to be linear. *Thorade* [1914] con-

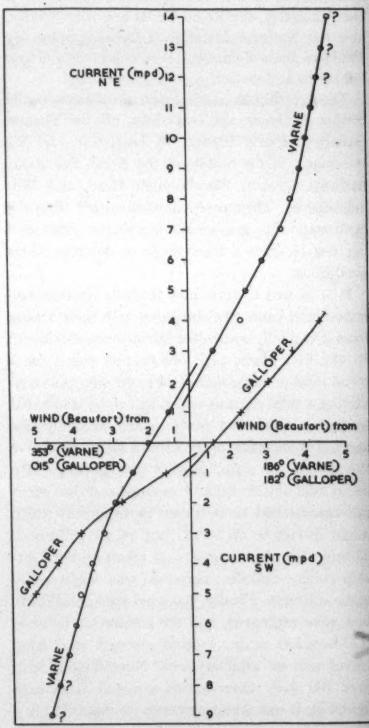

FIG. 3 – Wind-current relationship at VARNE and GALLOPER

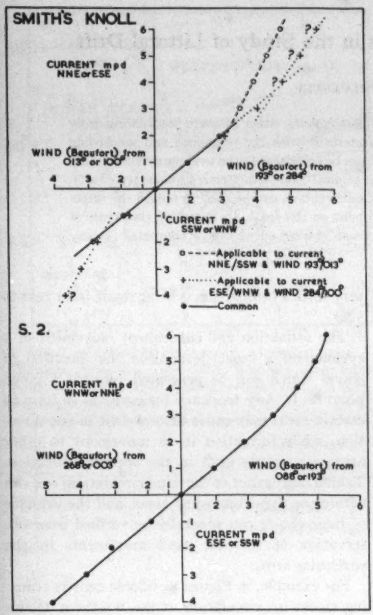
SMITH'S KNOLL
CURRENT mpd NNE or ESE
WIND (Beaufort) from 013° or 100°
WIND (Beaufort) from 193° or 284°
CURRENT mpd SSW or WNW
Applicable to current NNE/SSW & WIND 193°/013°
Applicable to current ESE/WNW & WIND 284°/100°
Common
S. 2.
CURRENT mpd WNW or NNE
WIND (Beaufort) from 268° or 003°
WIND (Beaufort) from 088° or 193°
CURRENT mpd ESE or SSW

FIG. 4 – Wind-current relationship at SMITH'S KNOLL and S. 2

cluded that at wind strengths less than Beaufort 3 the connecting expression, in the open ocean, was parabolic, and above that linear. There is a measure of agreement in the plots with Thorade, but no trace of the parabola is discernible. At the VARNE the plots are linear (mean current speed = 1.75 pct of wind speed) up to Beaufort 3 or 3-4. Although the points for the highest wind strengths are not very reliable, it does appear that a second linear expression comes into force above Beaufort 4 (mean current speed = 4.25 pct of wind speed). At the GALLOPER the curves are linear to about Beaufort 3-4, after which there is a good suggestion of a change in the connection for northerly winds but only a faint one for southerly winds.

In the plots (Fig. 4) for SMITH'S KNOLL and S.2 the basic current has been removed by transferring the current origins of Figure 2 to the wind origins. To eliminate the effect of the different times spent by the tidal streams in the various octants in the values of the water/wind percentages, the wind axes selected are those about which the time the tidal stream spends in various octants is evenly distributed. There is a very strong indication at SMITH'S KNOLL that the linearity of the connecting expression changes at Beaufort 3 (winds from 100° and 193°) or between 4 and 5 (winds from 284°), but the points for the last-named wind are a little doubtful. The points for the selected winds at S.2 are so close that they have been averaged to give one curve; there is little suggestion of change for winds from 268° or 003°, but quite a strong one, at a little over Beaufort 3, for winds from 088° and 193°.

Considering the plots as a whole, it seems that Beaufort 3 (250 mi/lunar day) marks a critical point in the relationship between wind and current. It also appears possible that the change is from one linear expression to another, in which case it is conceivable that the transition point is the same as that observed by Thorade in the changeover from parabolic to linear relationship. If not, then certain of the curves suggest that the relationship may be a rapidly convergent power series.

It is hoped in due course to make a further analysis of data gathered in 1955, when water movements were recorded by a method which, it is believed, eliminates some of the errors possible with the old method.

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The Use of Cyclonicity Charts in the Study of Littoral Drift

RICHARD SILVESTER

Abstract—It is useful in checking littoral drift movements, either by wave hindcasting or by site surveying, to correlate the period of measurement with the preceding and succeeding years. In this manner the net drift for the period can be compared to the average over a number of years, or its value can be viewed within the general long-term trend. Cyclonicity charts, which indicate the position and duration of cyclonic centers, can be used to obtain the direction of ocean waves generated towards a given point on the coast. By summing the hours of cyclonicity in areas causing drift up or down a coast, the net effect can be computed for any length of time.

Introduction—Littoral drift movement on the southwest coast of Western Australia was studied recently by hindcasting ocean waves for two points on the coast [*Darbyshire*, 1952; *Silvester*, 1955]. The data referred to wave height, wave period, wave direction, and duration of waves. Weather charts for the years 1951 and 1952 were used in the analysis.

It appeared desirable to check the seasonal cycle for these two years against that for the ten-year period for which cyclonicity charts were available, in order to study the uniqueness or otherwise of the results obtained. It was also desirable to find out if these results were part of a long term cycle.

Cyclonicity charts—The normal three-hourly synoptic charts, used for weather forecasting, are generally analyzed at the Central Meteorological Office, and one of the resultant summaries is the position and duration of cyclonic centers for the continent [*Karelsky*, 1954]. The occurrence of centers in five-degree quadrangles of latitude and longitude is recorded for the month as a number of hours' duration and written in the 'squares.'

Part of such a chart is illustrated in Figure 1, which shows the cyclonicity near the southwest coast of Western Australia for July 1955. The isopleths joining points of equal intensity are not used in the method described herein.

Cyclones (used in the general sense of low-pressure centers) cause strong winds which generate ocean waves toward any particular point on the coast from many directions. Anticyclones, on the other hand, cause weak winds which generate waves from more or less a constant direction. The only other prime mover of littoral drift is the sea breeze, which cannot be identified on synoptic charts. Therefore a study of net littoral drift can be carried out with cyclonicity charts alone. The effect of anticyclonicity and sea breezes could be added to the result if desired, but this should not be necessary since a comparison is being made from year to year.

The formation and subsequent movement of a cyclone off a coast determines the direction of waves which will be generated towards a given point on it. Any tendency for cyclones to form in certain areas may cause littoral drift in one direction, while formation in or movement to other areas may cause drift in the opposite direction. Taking cognizance of the wind circulation, one can determine these 'opposing' areas, and the veracity of their choice can generally be verified from observation of seasonal sand movements in the particular area.

For example, in Figure 1 cyclonic centers (causing clockwise circulation in the Southern Hemisphere) which occur in the area bounded by 30° to 40°S and 105° to 115°E should cause waves from northerly directions for the section of coast under study (hatched). There would result a southerly drift. Similarly, centers located in the area bounded by 30° to 40°S and 115° to 120°E should cause waves from southerly directions resulting in northerly drift.

The difference in the number of hours of cyclonicity in these two areas should be indicative of the tendency for drift in either direction. It is no measure of actual drift since the types of waves generated throughout the life of a cyclone change rapidly, but it serves as a seasonal or yearly comparison.

Seasonal fluctuations—Cyclonicity charts were available in this instance for the years 1946–55 inclusive. Monthly values of cyclonicity have been plotted in Figure 2. The excessive scatter of the points has been overcome in part by consideration of the medians. The differences in the two traces indicate a net southerly drift during winter and a net northerly drift during summer, a fact borne out by observation.

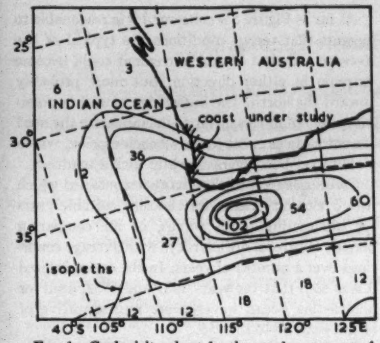

FIG. 1 – Cyclonicity chart for the southwest coast of Western Australia, July 1955; numbers give total hours per month that cyclonic centers occur in each five degree quadrangle

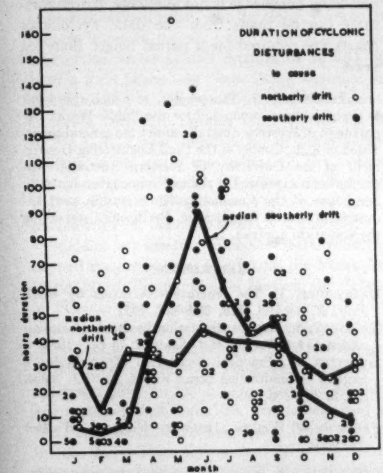
DURATION OF CYCLONIC DISTURBANCES to cause northerly drift southerly drift
median southerly drift
median northerly drift
hours duration
month
J F M A M J J A S O N D

FIG. 2 – Monthly values of cyclonicity to cause northerly and southerly drift in the vicinity of Fremantle, Western Australia

Differences of duration in the two areas have been averaged and plotted in Figure 3. A curve fitted to this data took the form

$$T = 2.3 + 21.7 \cos \theta$$

where T is duration in hours per month, and
θ is time variant, one year being 360° with the origin occurring between December and January.

A positive value of T indicates net northerly drift. The seasonal change indicated by this curve is true to nature on an average. It could be stated, therefore, that the areas chosen on the cyclonicity chart give a true picture of the littoral drift for the section of coast under study.

Since a comparison of monthly values for the years 1951 and 1952 with those over the longer period was desired, they have been plotted in Figure 3. It is seen that, although the general trend has been reproduced, conditions during any particular month could be grossly abnormal. The value for Decembers of 1951 and 1952 was found to be quite unique when checked in the records. This was

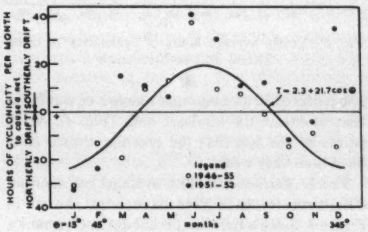

FIG. 3 – Monthly average of hours of cyclonicity to cause littoral drift at Fremantle

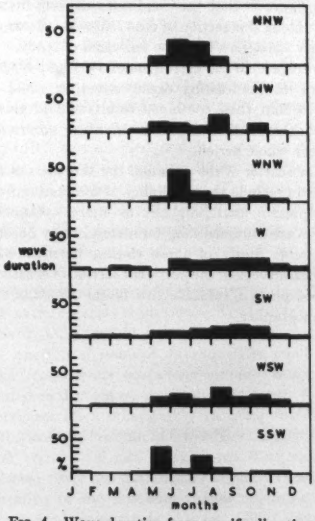

FIG. 4 – Wave duration from specific directions at Fremantle for the years 1951–1952

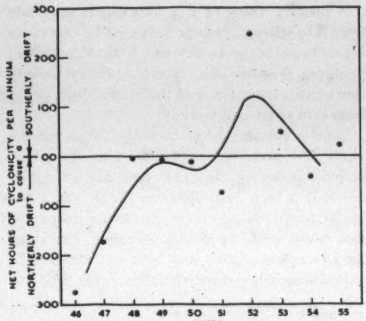

FIG. 5 – Yearly average hours of cyclonicity to cause littoral drift at Freemantle

not reflected in an abnormal number of waves for that month in the hindcast data (Fig. 4), which points to the fact that the cyclonic centers must have been very weak.

Yearly fluctuations—The averages of monthly differences for each year have been plotted in Figure 5. Since a ten-year period did not warrant a fitted curve, a smooth curve only has been sketched. The conclusion that may be drawn from this figure is that the conditions causing littoral drift along this section of coast showed substantial yearly variations over the ten years of study.

In regard to the usefulness of 1951 and 1952 as years for hindcasting ocean waves, it could be stated that their combined results should give a reasonably balanced picture of wave occurrence for the whole period.

The scatter of the data and the shortness of the record preclude the possibility of forecasting from the present material, but as more cyclonicity charts are obtained long term trends may become apparent. Study of these charts, together with annual surveys of the pertinent section of coastline, should place a valuable tool in the hands of the oceanographer.

As far as Figure 5 is concerned it is reasonable to suggest that recent conditions are typical of the average and that littoral movement could become extreme in either direction, but most probably toward the north. The knowledge of such a possibility served in this instance to emphasize the need for works to prevent further beach erosion, which would have been aggravated by such a tendency.

Conclusions—A method has been outlined which uses cyclonicity charts for choosing suitable years for hindcasting ocean waves, or for comparing periods of littoral drift surveys with average conditions over a number of years. In the example cited it was seen that the years 1951 and 1952, used for hindcasting ocean waves, were representative of of the years 1946 to 1955.

Assumptions in the choice of 'areas' can be verified by observation of seasonal sand movements whence yearly trends can be traced even when first-hand knowledge is not available. Before forecasts can be made from the data, cyclonicity charts are required for a period longer than ten years.

Acknowledgments—The project, of which this work is part, has been conducted for the Public Works Department of Western Australia under the general supervision of K. L. Cooper of the Civil Engineering Department of the University of Western Australia. Appreciation is expressed of the assistance given by N. S. Stenhouse of the Commonwealth Scientific, and Industrial Research Organization Perth office respecting the statistical analysis.

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Uranium Determination in Sea Water

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Abstract—Uranium analyses of sea-water samples taken from different locations were carried out by the isotope-dilution method. Uranium was separated by liquid-liquid extraction from 2000 ml of sea water, for each determination. The small residue of uranium resulting from the chemical separation was analyzed by mounting it on a tantalum filament and examining the UO_2^+ thermal ions in a Nier six-inch radius, 60° sector-type mass spectrometer. The results show a concentration of 3.1 to 3.5 micrograms of uranium per kilogram of sea water, with a uranium/salinity ratio of 9.0 to 9.8 $\times 10^{-6}$.

Introduction—A number of investigators have studied the relationship of the radioelements in ocean waters and ocean bottom sediments [*Joly*, 1908; *Pettersson*, 1937; *Föyn* and others, 1939; *Piggot* and *Urry*, 1941; *Rona* and *Urry*, 1952; *Holland* and *Kulp*, 1954; *Kröll*, 1954]. The radium content was found to be a fraction of that which would be present in equilibrium with the reported uranium content found in the sea water. The radium content of sea water is well established as 0.31×10^{-13} g Ra/l [*Rona* and *Urry*, 1952]. Uranium as determined by a number of authors shows considerable variation, ranging from 0.7 to 3.6×10^{-6} g U/l. A new investigation of the uranium content of sea water was indicated. The isotope dilution method [*Hayden, Reynolds*, and *Inghram*, 1949; *Inghram*, 1953] gave promise of being an improvement over the older methods of analysis.

Selection of samples—Samples were collected beyond the continental shelf, from the North Atlantic, North Pacific, Gulf of Mexico, and Straits of Florida. The samples were taken either with Nansen bottles or by direct syphoning through tygon tubing. The samples were stored and shipped in polyethylene carboys. These were rinsed with sea water prior to filling. The sea-water samples were not acidified. Salinities were determined at the Department of Oceanography, Texas A & M, by the radio-frequency method [*Harwell*, 1954]. Chemical processing was carried out in the trace-level laboratories of the Oak Ridge Institute of Nuclear Studies, reserved entirely for experiments with sea water, and samples were kept free as possible from radioactive contaminations.

METHOD OF DETERMINATION

In the isotope-dilution method using the mass spectrometer a standard of known isotopic ratio in solution is added to the sample. This standard, commonly called 'spike' is enriched in U^{235}. After the 'spike,' is added to the sea water, it will show a new isotopic ratio. The ratios of U^{235} to U^{238} in the 'spike,' in the normal sample, and in the recovered uranium permit the calculation of the uranium concentration. As the ratio U^{235} to U^{238} is the same in any portion of the sample, a quantitative separation of uranium is not necessary; however, because of the very low concentration of uranium in sea water, it is advisable to concentrate as much of the uranium as possible. The yield of each step of the chemical separation was checked by adding U^{233} as a tracer. This uranium isotope has a relatively short half life of 1.65×10^5 *y*. Its high specific activity and alpha particles of high energy make its detection easy in an ionization or proportional counter. It should be noted that the use of an electron multiplier in the mass spectrometer, if it were available, would have reduced the sample required by a factor of 100.

Chemical separation—A flow diagram of the liquid-liquid extraction process is shown in Figure 1. The operations were performed with glass separatory funnels. Neither the organic solvents nor the $(NH_4)_2CO_3$ were specially purified. The HNO_3 and HCl were distilled, and the water was distilled three times in pyrex glass. Where possible, polyethylene containers were used. The glassware was cleaned by prolonged boiling in concentrated HNO_3. The blank determinations were made by processing the spike solution in 1000 ml of pure water and measuring any detectable change in the isotopic ratio caused by uranium contamination from the reagents or glassware. The results of these blanks are shown in Table 1.

Analysis of uranium isotopes—The small nitric acid concentrate containing uranium was evaporated to dryness on a tantalum filament. A small stainless steel subassembly carrying this loaded filament was introduced into a Nier six-inch radius, 60° sector-type mass spectrometer. Ions were generated from this filament by regulated resistance heating of the tantalum ribbon mounting at an estimated temperature of about 1800°C, as measured by an optical pyrometer. The UO_2^+ thermal

ions were used as a basis for analysis. The ion intensity was measured by a vibrating reed electrometer, measuring the signal developed across a 10^{10}-ohm resistor. The amplified current was then recorded by a 0 to 10 ma, rapid response, strip chart recorder. The data were reduced from the chart by geometric construction and manual measurement. The ion-recording system was calibrated with known signals, generated by a student type potentiometer and a standard cell, and also by examining known isotopic mixtures of uranium, prepared by mixing solutions of nearly 100 pct pure isotopes. These tests led to the conclusion that the errors of analysis should not be greater than 0.5 pct because of any bias in the mass spectrometer including the source. More significant errors were caused by the relatively high uranium concentration of the blanks. In general, data were taken for the intensities of U^{233}, U^{235}, and U^{238} isotopes. The U^{233} contained 1.96 pct of U^{236} as an impurity; hence, a small correction was made for each case in which it was used as tracer. The enriched uranium standard consisted of specially refined uranium which contained 99.94 mole pct U^{235} and 0.04 mole pct U^{238}.

Calculations—The ratio measured in the mass spectrometer is

$$R = \frac{U^{235}}{U^{238}} = \frac{U_s^{235} + U_n^{235}}{U_s^{238} + U_n^{235}} = \frac{W_s A_s^{235}/M_s + W_n A_n^{235}/M_n}{W_s A_s^{238}/M_s + W_n A_n^{238}/M_n} \quad (1)$$

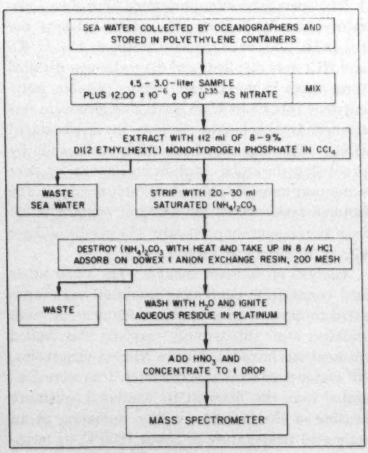
SEA WATER COLLECTED BY OCEANOGRAPHERS AND STORED IN POLYETHYLENE CONTAINERS
1.5 – 3.0-liter SAMPLE PLUS 12.00 x 10⁻⁶ g OF U²³⁵ AS NITRATE
MIX
EXTRACT WITH 12 ml OF 8–9% DI(2 ETHYLHEXYL) MONOHYDROGEN PHOSPHATE IN CCl₄
WASTE SEA WATER
STRIP WITH 20–30 ml SATURATED (NH₄)₂CO₃
DESTROY (NH₄)₂CO₃ WITH HEAT AND TAKE UP IN 8 N HCl ADSORB ON DOWEX 1 ANION EXCHANGE RESIN, 200 MESH
WASTE
WASH WITH H₂O AND IGNITE AQUEOUS RESIDUE IN PLATINUM
ADD HNO₃ AND CONCENTRATE TO 1 DROP
MASS SPECTROMETER

FIG. 1 – Uranium analysis of sea water, concentration procedure

TABLE 1 – *The uranium content of waters by isotope dilution analysis*

Body of water examined	Location	Uranium content $\times 10^6$ g/l	Average uranium content	Remarks
Mississippi	St. Louis	1.83 1.83	1.83	Filtered
Missouri	St. Louis	2.33 2.45	2.39	Filtered
Blanks		0.103 0.2 0.2 0.15 0.14 0.17 0.14	0.14	Complete procedure
		0.023 0.024	0.024	Complete procedure omitting the resin step

where U^{238} = moles of U^{238}
U^{235} = moles of U^{235}
n = natural uranium
A = isotopic concentration in mole percent
R = ratio measured in the mass spectrometer
W = weight
M = atomic weight
s = enriched uranium 'spike'

which yields

$$W_n = W_s \frac{M_n}{M_s}\left(\frac{A_s^{235} - RA_s^{238}}{RA_n^{238} - A_n^{235}}\right) \quad (2)$$

and, inserting constants, reduces to

$$W_n = W_s 1.0125\left(\frac{99.94 - R0.04}{R99.28 - 0.71}\right) \quad (3)$$

RESULTS

The results are summarized in Table 2. It can be seen that the uranium values for the surface waters of the Gulf of Mexico are higher than those of the North Atlantic and North Pacific Oceans. The deep-water samples of the Gulf of Mexico contain uranium values similar to those of the North Atlantic and North Pacific Oceans. The reasons for the above differences are open to speculation. There is evidence (unpublished data, Department of Oceanography, Texas A and M) that the bottom water of the Gulf of Mexico originates from waters of the Atlantic Ocean.

The results reported here are a strong indication that the surface and deep waters of the Gulf of Mexico are of different water masses. However

TABLE 2 – *The uranium content of sea waters by isotopic dilution analysis*

Water body	Depth	Latitude Longitude	Salinity	Uranium content $\times 10^6$	Average uranium content $\times 10^6$	Uranium-salinity ratio $\times 10^6$
	m	° ′	‰	‰	‰	
Gulf of Mexico	1–30	26 52 N 95 04 W	36.2	3.57 3.44 3.53 3.49	3.51	9.70
Gulf of Mexico	1–30	28 20 N 88 21 W	35.7	3.43 3.57 3.44	3.48	9.75
Gulf of Mexico	1800	21 38 N 85 47 W	34.5	3.32 3.20	3.26	9.45
Gulf of Mexico	2000	23 51 N 83 03 W	35.0	(2.69) 3.20	3.20	9.14
Gulf of Mexico	600	27 53 N 86 35 W	34.9	3.15 3.10	3.13	8.97
Straits of Fla. (Miami)	1–30	25 49 N 79 55 W	36.2	3.47 3.43	3.45	9.53
N. Atlantic (Beaufort)	1–30	34 21 N 76 34 W	36.1	3.26 3.32 3.16 3.29 3.28[a]	3.26	9.03
N. Atlantic (Woods Hole)	1–30	37 04.5 N 66 54.5 W	36.2	3.39 3.53 3.01 3.36	3.30	9.12
N. Pacific	1–30	29 41 N 120 48 W	33.5	3.03 3.32 3.28	3.21	9.58
Average					3.31	

[a] Corrected for 3.62 μg of added uranium.

considerably more information regarding the current system of the Gulf of Mexico is necessary to substantiate these findings. It is unfortunate that the authors had no access to deep water samples from the North Atlantic and North Pacific Oceans.

In Table 3, data for uranium concentration were compiled from the literature. The uranium determinations which were taken for comparison were those made at locations neighboring ones in this study. It can be seen that the results obtained by *Hernegger* and *Karlik* [1935], *Rona* and *Urry* [1952], and *Koczy* [1950], by the fluorometric method, are lower than those of *Nakanishi* [1952] and *Smith* and *Grimaldi* [1954]. The results of *Stewart* and *Bentley* [1954] are significantly higher than either of these. The latter counted fission fragments of U^{235} in samples exposed to the slow neutron flux of the heavy water reactor of the Argonne National Laboratory. The authors' values are the highest reported to date. This result is not surprising since of all the methods used only the isotope-dilution method can tolerate losses in the chemical separation without adversely affecting the results. Such losses would result in lower concentrations by the other methods.

River water—The uranium concentrations of river waters as reported in Table 1 are not expected to be constant. Unpublished results of F. Hecht [*Koczy*, 1954] indicate a range of 0.3 to 20 $\times$ 10^{-6} g U/l in Swedish river waters. The concentrations of uranium determined by the authors for two rivers within a distance of 35 mi fall well within this range.

TABLE 3 – *The uranium content of sea waters, 0–30 meters*

Water body	Latitude Longitude	Uranium $\times 10^6$ g/kg	Method	Reference
	° ′			
N. Pacific	37 21 N 112 45 W	1.1	Fluorometric	*Koczy*, 1950
N. Pacific	31 49 N 135 34 W	1.91	Fluorometric	*Nakanishi*, 1952
N. Pacific	San Francisco, California	2.43	Fission count	*Stewart* and *Bentley*, 1954
N. Pacific	29 41 N 120 48 W	3.21	Isotope dilution	This paper
N. Atlantic	73 10 N 00 32 W	1.02	Fluorometric	*Koczy*, 1950
N. Atlantic	40 07 N 67 12 W	0.73	Fluorometric	*Rona* and *Urry*, 1952
N. Atlantic	Ocean City, Md.	1.12	Fluorometric	*Smith* and *Grimaldi*, 1954
N. Atlantic	37 05 N 66 55 W	3.30	Isotope dilution	This paper
N. Atlantic	34 21 N 76 34 W	3.26	Isotope dilution	This paper
N. Atlantic	73 20 N 00 32 W	1.1	Fluorometric	*Hernegger* and *Karlik*, 1935
Straits of Florida	25 49 N 79 55 W	3.45	Isotope dilution	This paper
Gulf of Mexico	26 52 N 95 04 W	3.51	Isotope dilution	This paper
Gulf of Mexico	28 20 N 88 21 W	3.48	Isotope dilution	This paper
Gulf of Mexico	28 02 N 80 33 W	2.93	Fluorometric	*Smith* and *Grimaldi*, 1954

DISCUSSION

The most important aspect of uranium and radium determinations in sea water and deep ocean sediment is the fact that they depart from radioactive equilibrium. In radioactive equilibrium 3.49×10^{-7} g radium is in equilibrium with one gram of uranium. Accepting the average value of 3.3×10^{-6} ‰ of uranium in sea water found by the authors, we calculate the equilibrium amount of radium in sea water to be 11.5×10^{-13} ‰. The average value for radium in sea water, however, is 0.3×10^{-13} ‰ [*Rona* and *Urry*, 1952], or about 2.6 pct of the equilibrium value. The surface layers of the deep ocean deposits, on the other hand, are rich in radium which is not supported by uranium. *Pettersson* [1937] was the first to propose a mechanism to explain this condition. He suggested that Th^{230}, the parent of radium, is removed from the sea water by an effective precipitation mechanism as it is formed from dissolved uranium. Since radium is derived in the surface layers from Th^{230}, it decays with the half life of Th^{230} (8×10^4y). These facts permit the submarine geochronology of the ocean sediments to be determined by measuring the radium content of ocean bottom cores at various depths below the surface [*Piggot* and *Urry*, 1941; *Kröll*, 1954].

Extensive investigations of bottom sediments were undertaken by *Kröll* [1953] on cores taken from great depths of the central Pacific Ocean with

the *Albatross* (during the Swedish Expedition in 1947–48). Kröll carried out an integration of the total radium content in a sediment core down to levels where practically all the Th^{230} precipitated from the supernatant water column has had time to become disintegrated; thus, generally only very small quantities of uranium-supported radium are present. This permits a comparison between excess radium in the upper sediment layers and the potential supply of radium derivable from the uranium in the superimposed column of sea water.

There appears to be a surplus of sediment radium over that to be expected from Th^{230} precipitated from supernatant uranium by a factor of 1.5 to 3. Kröll feels that this is outside the limits of experimental error and may be due to a higher content of dissolved uranium in the ocean in recent geological times than at present. His calculations were based on G. Koczy's uranium value of 1.3×10^{-6}‰. (These radium calculations, when converted to the uranium range needed in sea water to account for Kröll's observed radium content, range from 2.0 to 3.9×10^{-6}‰).

The authors' average uranium value for the Pacific and Atlantic oceans is 3.3×10^{-6}‰, well within Kröll's limits. This value allows a satisfactory explanation of the radium balance in the Pacific cores without resorting to any assumption about variation in the uranium content of the ocean with time [*Kröll*, 1954].

Acknowledgments—The authors wish to acknowledge the help of the following for securing the sea water samples: Woods Hole Oceanographic Institution, Woods Hole, Massachusetts; Scripps Institution of Oceanography, La Jolla, California; Department of Oceanography, Agricultural and Mechanical College, Texas; and Walter A. Chipman, Fish and Wildlife Service, Beaufort, North Carolina. We also wish to thank August V. Graf, Water Division, Howard Bend Station, Chesterfield, Missouri, for securing the river samples for us; Willis H. Baldwin, Oak Ridge National Laboratory, for his suggestions concerning the chemical separation; G. R. Tilton of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, who measured some isotopic ratios with a mass spectrometer equipped with an electron multiplier as a cross check; and Russell Baldock for his helpful suggestions and encouragement.

The uranium extraction procedure using di(2-ethylhexyl) phosphoric acid was developed by the Raw Materials Section of the Materials Chemistry Division of Oak Ridge National Laboratory [*Blake, Brown,* and *Coleman*, 1955]. This paper is based in part on work performed for the U. S. Atomic Energy Commission by Union Carbide Nuclear Company, a Division of Union Carbide and Carbon Corporation, at the Oak Ridge National Laboratory, and by the Oak Ridge Institute of Nuclear Studies.

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Analysis of Data From Pumping Tests In Leaky Aquifers

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Abstract—Graphical methods are outlined for determining the coefficients of transmissibility, storage, and leakage of an effectively infinite leaky artesian aquifer. The procedure is based on the theory, developed by Hantush and Jacob, of the nonsteady flow toward a steadily discharging well from an infinite leaky aquifer. Applications of these methods are illustrated by treating data from the Roswell artesian basin in New Mexico.

Introduction—Based on the non-equilibrium theory developed by *Theis* [1935], several methods have been developed for determining the field values of the transmissibility and storage coefficients of non-leaky aquifers. Notable among these are Theis' graphical method first described by *Jacob* [1940], Theis' recovery method first described by *Wenzel* [1942], Jacob's generalized graphical methods [*Cooper* and *Jacob*, 1946], *Jacob's* [1946a] method for determining well loss, and *Chow's* [1952] graphical method. *Jacob* and *Lohman* [1952] advanced the theory of non-steady flow to a well of constant drawdown and developed a graphical method by which the formation constant can be determined from data obtained from tests in such type of flow.

The solution of non-steady distribution of drawdown caused by pumping a well at a constant rate from an effectively infinite and perfectly elastic aquifer of uniform thickness in which leakage takes place in proportion to the drawdown was obtained by *Hantush* and *Jacob* [1955]. It is expressed by one of the following relations

$$s = (Q/4\pi T) \cdot \int_u^\infty (1/y) \exp(-y - r^2/4B^2y)\, dy \quad (1a)$$

$$= (Q/4\pi T)\left[2K_0(r/B) - \int_q^\infty (1/y) \exp(-y - r^2/4B^2y)\right] dy \quad (1b)$$

$$= (Q/4\pi T)W(u, r/B) \quad (1c)$$

where $u = r^2S/4Tt$; $q = (r^2/4B^2)/u = Tt/SB^2$; and where s = drawdown (or recovery); Q = discharge of well; T = transmissibility coefficient; S = storage coefficient; $B = \sqrt{Tb'/K'}$, called leakage factor [*Hantush* and *Jacob*, 1954]; K', b' are the hydraulic conductivity and the thickness of the semi-confining bed through which leakage occurs; r = distance from center of well to any point in the field; and t = time since pumping began, or, for recovery, since shutdown; K_0 is the modified Bessel function of the second kind and of zero order; $W(u, r/B)$ may be called the 'well function' for leaky systems.

The maximum drawdown or the steady-state distribution of drawdown in the vicinity of such a well is obtained from (1b) by letting t approach infinity. So

$$s_m = (Q/2\pi T)K_0(r/B) \quad (2)$$

where s_m is the maximum drawdown or recovery.

In addition to the storage and transmissibility coefficient, a third formation constant appears in treating problems in leaky systems. This constant characterizes the ability of the semi-confining bed to transmit upward or downward leakage. The constant is called 'leakance' or the leakage coefficient, and is symbolized by K'/b' [*Hantush* and *Jacob*, 1955]. In terms of the above notation, the leakage coefficient, or K'/b', is

$$K'/b' = T/B^2 \quad (3)$$

The leakage coefficient, or 'leakance,' may be defined as the quantity of flow that crosses a unit area of the interface between the main aquifer and its semi-confining bed, if the difference between the head in the main aquifer and in that supplying leakage is unity.

Based on the solution represented by (2), *Jacob* [1946b] described a method for obtaining field values of T and B, and hence of K'/b'. The method is a modification of Theis' graphical method. In this case, however, the 'type curve' is a plot of the function $K_0(x)$ against x on logarithmic paper, and the observational data (data on the steady distribution of drawdown in the vicinity of a well or a pumping center) are plotted on logarithmic paper of the same scale with r as abscissa and s as ordinate.

It is the purpose of this paper to use (1) and (2) in outlining graphical methods by which pumping test data may be used in obtaining the field values

of the formation constants, namely, the coefficients of storage, of transmissibility, and of leakage.

Steady Distribution of Drawdown

A graphical method based on the steady distribution of drawdown in the vicinity of a steadily discharging well is discussed below.

Theory—When r/B is small ($r/B \leq 0.05$), (2) may, for practical purposes, be approximated by

$$s_m \approx (2.3\ Q/2\pi T)\log_{10}(0.89\ r/B) \qquad (4)$$

Thus a plot of s_m against r on semi-logarithmic paper, with r on the logarithmic scale, will exhibit a straight-line relationship in the range where r/B is small. In the range where r/B is large, the points fall on a curve that approaches the zero-drawdown axis asymptotically. The slope of the straight portion of the curve, or $\Delta s/\Delta\log_{10}r$, is equal to $2.3Q/2\pi T$. The intercept r_0 of this line on the zero-drawdown axis is given by $B = 0.89r_0$.

Application—If data from a pumping test are plotted on semi-logarithmic paper and most of the points fall on a straight line (several points are necessary to establish this condition), the procedure for computing T, B, and then the leakage coefficient is as follows: (1) Construct the best-fit straight line through the points which appear to fall on a straight line, and measure its slope ($\Delta s/\Delta\log_{10}r$). (2) Compute T from the relation $T = 2.3Q/(2\pi\Delta s/\Delta\log_{10}r)$. (3) Select any point on the line and note its coordinates s and r. Substitute these values in (4) and solve for B, or determine r_0, the intercept on the zero-drawdown axis, and then compute B from the relation $B = 0.89r_0$. (4) Compute the leakage coefficient from (3).

Non-Steady Distribution of Drawdown

Theory—The theoretical graph of the drawdown s against the time t on semi-logarithmic paper with t plotted in the logarithmic scale as in Figure 1, has the following properties:

The slope m at any point is given by

$$m = \Delta s/\Delta\log_{10}t = (2.3Q/4\pi T)\exp(-u - r^2/4B^2u) \qquad (5)$$

Eq. (5) is obtained by differentiating (1) with respect to $\log_{10}t$.

The curve has an inflection point at which the following relations hold

$$\text{(a)} \qquad u_i = r^2S/4Tt_i = r/2B \qquad (6)$$

where the subscript i pertains to values of the variables at the inflection point. The above relation is obtained by equating to zero the second derivative of s with respect to $\log_{10}t$, and solving for u.

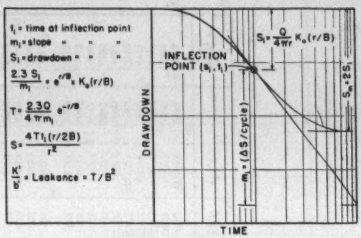
t_i = time at inflection point
m_i = slope " " "
S_i = drawdown " " "
$\frac{2.3\,S_i}{m_i} = e^{r/B} = K_0(r/B)$
$T = \frac{2.30}{4\pi m_i}\,e^{-r/B}$
$S = \frac{4Tt_i(r/2B)}{r^2}$
$\frac{K'}{b'}$ = Leakance = T/B^2
INFLECTION POINT (s_i, t_i)
$S_i = \frac{Q}{4\pi T}K_0(r/B)$
$S_m = 2S_i$
$m_i = (\Delta S/s\text{ cycle})$
DRAWDOWN
TIME

FIG. 1.—Variation of drawdown with time due to a steadily discharging well from an infinite leaky aquifer

(b) The slope of the curve m_i at the inflection point is given by

$$m_i = (2.3Q/4\pi T)e^{-r/B} \qquad (7)$$

or

$$r = 2.3B[\log_{10}(2.3Q/4\pi T) - \log_{10}m_i] \qquad (8)$$

which is obtained by substituting the value of u_i from (6) in (5)

(c) The drawdown at the inflection poing s_i is given by

$$s_i = (Q/4\pi T)K_0(r/B) = (\tfrac{1}{2})s_m \qquad (9)$$

This is obtained as follows: In equation (1a), substitute for u the value $r/2B$ to obtain s_i, or

$$s_i/(Q/4\pi T) = \int_{(r/2B)}^{\infty}(1/y)\exp(-y - r^2/4B^2y)\,dy \qquad (10)$$

And if the value of u_i from (6) is substituted for u in (1b), then s_i will be given also by

$$s_i/(Q/4\pi T) = 2K_0(r/B) - \int_{(r/2B)}^{\infty}(1/y)\exp(-y - r^2/4B^2y)\,dy \qquad (11)$$

From (10) and (11), the relation in (9) is immediately established.

(d) the relation between the drawdown and the slope of the curve at the inflection point is given by

$$f(r/B) = e^{r/B}K_0(r/B) = 2.3\ s_i/m_i \qquad (12)$$

which is obtained by solving simultaneously (7) and (9) for $f(r/B)$.

(e) The curve is symmetrical with respect to the inflection point and the drawdowns at the

TABLE 1 – *Values of the functions* e^x, $K_0(x)$, $e^xK_0(x)$, $-Ei(-x)$, *and* $-Ei(-x)e^x$

x	e^x	$K_0(x)$	$e^xK_0(x)$	$-Ei(-x)$	$-Ei(-x)\,e^x$	x	e^x	$K_0(x)$	$e^xK_0(x)$	$-Ei(-x)$	$-Ei(-x)\,e^x$	x	e^x	$K_0(x)$	$e^xK_0(x)$	$-Ei(-x)$	$-Ei(-x)\,e^x$
0.010	1.0101	4.7212	4.7687	4.0379	4.0787	0.10	1.1052	2.4271	2.6823	1.8229	2.0147	1.0	2.7183	0.4210	1.1445	.2194	.5964
11	1.0111	4.6260	4.6771	3.9436	3.9874	11	1.1163	2.3333	2.6046	1.7371	1.9391	1.1	3.0042	.3656	1.0983	.1860	.5588
12	1.0121	4.5390	4.5938	3.8576	3.9044	12	1.1275	2.2479	2.5345	1.6595	1.8711	1.2	3.3201	.3185	1.0575	.1584	.5259
13	1.0131	4.4590	4.5173	3.7785	3.8282	13	1.1388	2.1695	2.4707	1.5889	1.8094	1.3	3.6693	.2782	1.0210	.1355	.4972
14	1.0141	4.3849	4.4467	3.7054	3.7578	14	1.1503	2.0972	2.4123	1.5241	1.7532	1.4	4.0552	.2437	0.9881	.1162	.4712
15	1.0151	4.3159	4.3812	3.6374	3.6925	15	1.1618	2.0300	2.3585	1.4645	1.7015	1.5	4.4817	.2138	.9582	.1000	.4482
16	1.0161	4.2514	4.3200	3.5739	3.6317	16	1.1735	1.9674	2.3088	1.4092	1.6537	1.6	4.9530	.1880	.9309	.0863	.4275
17	1.0171	4.1908	4.2627	3.5143	3.5746	17	1.1853	1.9088	2.2625	1.3578	1.6094	1.7	5.4739	.1655	.9059	.0747	.4086
18	1.0182	4.1337	4.2088	3.4581	3.5209	18	1.1972	1.8537	2.2193	1.3098	1.5681	1.8	6.0496	.1459	.8828	.0647	.3915
19	1.0192	4.0797	4.1580	3.4050	3.4705	19	1.2093	1.8018	2.1788	1.2649	1.5295	1.9	6.6859	.1288	.8614	.0562	.3758
0.020	1.0202	4.0285	4.1098	3.3547	3.4225	0.20	1.2214	1.7527	2.1408	1.2227	1.4934	2.0	7.3891	.1139	.8416	.0489	.3613
21	1.0212	3.9797	4.0642	3.3069	3.3771	21	1.2337	1.7062	2.1049	1.1829	1.4593	2.1	8.1662	.1008	.8230	.0426	.3480
22	1.0222	3.9332	4.0207	3.2614	3.3340	22	1.2461	1.6620	2.0710	1.1454	1.4273	2.2	9.0250	.0893	.8057	.0372	.3356
23	1.0233	3.8888	3.9793	3.2179	3.2927	23	1.2586	1.6199	2.0389	1.1099	1.3969	2.3	9.9742	.0791	.7894	.0325	.3242
24	1.0243	3.8463	3.9398	3.1763	3.2535	24	1.2713	1.5798	2.0084	1.0762	1.3681	2.4	11.0232	.0702	.7740	.0284	.3135
25	1.0253	3.8056	3.9019	.3.1365	3.2159	25	1.2840	1.5415	1.9793	1.0443	1.3409	2.5	12.1825	.0623	.7596	.0249	.3035
26	1.0263	3.7664	3.8656	3.0983	3.1799	26	1.2969	1.5048	1.9517	1.0139	1.3149	2.6	13.4637	.0554	.7459	.0219	.2942
27	1.0274	3.7287	3.8307	3.0615	3.1452	27	1.3100	1.4697	1.9253	.9849	1.2902	2.7	14.8797	.0493	.7329	.0192	.2854
28	1.0284	3.6924	3.7972	3.0261	3.1119	28	1.3231	1.4360	1.9000	.9573	1.2666	2.8	16.4446	.0438	.7206	.0169	.2773
29	1.0294	3.6574	3.7650	2.9920	3.0800	29	1.3364	1.4036	1.8758	.9309	1.2441	2.9	18.1742	.0390	.7089	.0148	.2693
0.030	1.0305	3.6235	3.7339	2.9591	3.0494	0.30	1.3499	1.3725	1.8526	.9057	1.2226	3.0	20.0855	.0347	.6978	.0131	.2621
31	1.0315	3.5908	3.7039	2.9273	3.0196	31	1.3634	1.3425	1.8304	.8815	1.2018	3.1	22.1980	.0310	.6871	.0115	.2551
32	1.0325	3.5591	3.6749	2.8965	2.9908	32	1.3771	1.3136	1.8089	.8583	1.1820	3.2	24.5325	.0276	.6770	.0101	.2485
33	1.0336	3.5284	3.6468	2.8668	2.9631	33	1.3910	1.2857	1.7883	.8361	1.1630	3.3	27.1126	.0246	.6673	.0089	.2424
34	1.0346	3.4986	3.6196	2.8379	2.9362	34	1.4050	1.2587	1.7685	.8147	1.1446	3.4	29.9641	.0220	.6580	.0079	.2365
35	1.0356	3.4697	3.5933	2.8099	2.9101	35	1.4191	1.2327	1.7493	.7942	1.1270	3.5	33.1155	.0196	.6490	.0070	.2308
36	1.0367	3.4416	3.5678	2.7827	2.8848	36	1.4333	1.2075	1.7308	.7745	1.1101	3.6	36.5982	.0175	.6405	.0062	.2254
37	1.0377	3.4143	3.5430	2.7563	2.8603	37	1.4477	1.1832	1.7129	.7554	1.0936	3.7	40.4473	.0156	.6322	.0055	.2204
38	1.0387	3.3877	3.5189	2.7306	2.8364	38	1.4623	1.1596	1.6956	.7371	1.0779	3.8	44.7012	.0140	.6243	.0048	.2155
39	1.0398	3.3618	3.4955	2.7056	2.8133	39	1.4770	1.1367	1.6789	.7194	1.0626	3.9	49.4025	.0125	.6166	.0043	.2108
0.040	1.0408	3.3365	3.4727	2.6813	2.7907	0.40	1.4918	1.1145	1.6627	.7024	1.0478	4.0	54.5982	.0112	.6093	.0038	.2063
41	1.0419	3.3119	3.4505	2.6576	2.7688	41	1.5068	1.0930	1.6470	.6859	1.0335	4.1	60.3403	.0100	.6022	.0033	.2021
42	1.0429	3.2879	3.4289	2.6344	2.7474	42	1.5220	1.0721	1.6317	.6700	1.0197	4.2	66.6863	.0089	.5953	.0030	.1980
43	1.0439	3.2645	3.4079	2.6119	2.7267	43	1.5373	1.0518	1.6169	.6546	1.0063	4.3	73.6998	.0080	.5887	.0026	.1941
44	1.0450	3.2415	3.3874	2.5899	2.7064	44	1.5527	1.0321	1.6025	.6397	.9933	4.4	81.4509	.0071	.5823	.0023	.1903
45	1.0460	3.2192	3.3673	2.5684	2.6866	45	1.5683	1.0129	1.5886	.6253	.9807	4.5	90.0171	.0064	.5761	.0021	.1866
46	1.0471	3.1973	3.3478	2.5474	2.6672	46	1.5841	0.9943	1.5750	.6114	.9685	4.6	99.4843	.0057	.5701	.0018	.1832
47	1.0481	3.1758	3.3287	2.5268	2.6483	47	1.6000	.9761	1.5617	.5979	.9566	4.7	109.9472	.0051	.5643	.0016	.1798
48	1.0492	3.1549	3.3100	2.5068	2.6300	48	1.6161	.9584	1.5489	.5848	.9451	4.8	121.5104	.0046	.5586	.0014	.1766
49	1.0502	3.1343	3.2918	2.4871	2.6120	49	1.6323	.9412	1.5363	.5721	.9338	4.9	134.2898	.0041	.5531	.0013	.1734
												5.0	148.4132	.0037	.5478	.0011	.1704

0.050	1.0513	3.1142	3.2739	2.4679	2.5945
51	1.0523	3.0945	3.2564	2.4491	2.5773
52	1.0534	3.0752	3.2393	2.4306	2.5604
53	1.0544	3.0562	3.2226	2.4126	2.5440
54	1.0555	3.0376	3.2062	2.3948	2.5278
55	1.0565	3.0194	3.1901	2.3775	2.5120
56	1.0576	3.0015	3.1744	2.3604	2.4964
57	1.0587	2.9839	3.1589	2.3437	2.4811
58	1.0597	2.9666	3.1437	2.3273	2.4663
59	1.0608	2.9496	3.1288	2.3111	2.4516
0.060	1.0618	2.9329	3.1142	2.2953	2.4371
61	1.0629	2.9165	3.0999	2.2797	2.4230
62	1.0640	2.9003	3.0858	2.2645	2.4092
63	1.0650	2.8844	3.0719	2.2494	2.3956
64	1.0661	2.8688	3.0584	2.2346	2.3822
65	1.0672	2.8534	3.0450	2.2201	2.3691
66	1.0682	2.8382	3.0319	2.2058	2.3562
67	1.0693	2.8233	3.0189	2.1917	2.3434
68	1.0704	2.8086	3.0062	2.1779	2.3310
69	1.0714	2.7941	2.9937	2.1643	2.3188
0.070	1.0725	2.7798	2.9814	2.1508	2.3067
71	1.0736	2.7657	2.9693	2.1376	2.2949
72	1.0747	2.7519	2.9573	2.1246	2.2832
73	1.0757	2.7382	2.9455	2.1118	2.2717
74	1.0768	2.7247	2.9340	2.0991	2.2603
75	1.0779	2.7114	2.9226	2.0867	2.2492
76	1.0790	2.6983	2.9113	2.0744	2.2381
77	1.0800	2.6853	2.9002	2.0623	2.2273
78	1.0811	2.6726	2.8894	2.0503	2.2165
79	1.0822	2.6599	2.8786	2.0386	2.2062
0.080	1.0833	2.6475	2.8680	2.0269	2.1957
81	1.0844	2.6352	2.8575	2.0155	2.1856
82	1.0855	2.6231	2.8472	2.0042	2.1754
83	1.0865	2.6111	2.8370	1.9930	2.1655
84	1.0876	2.5992	2.8270	1.9820	2.1557
85	1.0887	2.5875	2.8171	1.9711	2.1460
86	1.0898	2.5759	2.8073	1.9604	2.1364
87	1.0909	2.5645	2.7976	1.9498	2.1270
88	1.0920	2.5532	2.7881	1.9393	2.1176
89	1.0931	2.5421	2.7787	1.9290	2.1086
0.090	1.0942	2.5310	2.7694	1.9187	2.0994
91	1.0953	2.5201	2.7602	1.9087	2.0906
92	1.0964	2.5093	2.7511	1.8987	2.0818
93	1.0975	2.4986	2.7421	1.8888	2.0729
94	1.0986	2.4881	2.7333	1.8791	2.0643
95	1.0997	2.4776	2.7246	1.8695	2.0558
96	1.1008	2.4673	2.7159	1.8599	2.0473
97	1.1019	2.4571	2.7074	1.8505	2.0390
98	1.1030	2.4470	2.6989	1.8412	2.0307
99	1.1041	2.4370	2.6906	1.8320	2.0227
0.100	1.1052	2.4271	2.6823	1.8229	2.0147

0.50	1.6487	.9244	1.5241	.5598	.9229
51	1.6653	.9081	1.5122	.5478	.9123
52	1.6820	.8921	1.5006	.5362	.9019
53	1.6989	.8766	1.4892	.5250	.8919
54	1.7160	.8614	1.4781	.5140	.8820
55	1.7333	.8466	1.4673	.5034	.8725
56	1.7507	.8321	1.4567	.4930	.8631
57	1.7683	.8180	1.4464	.4830	.8541
58	1.7860	.8042	1.4363	.4732	.8451
59	1.8040	.7907	1.4264	.4637	.8365
0.60	1.8221	.7775	1.4167	.4544	.8280
61	1.8404	.7646	1.4073	.4454	.8197
62	1.8589	.7520	1.3980	.4366	.8116
63	1.8776	.7397	1.3889	.4280	.8036
64	1.8965	.7277	1.3800	.4197	.7960
65	1.9155	.7159	1.3713	.4115	.7882
66	1.9348	.7043	1.3627	.4036	.7809
67	1.9542	.6930	1.3543	.3959	.7737
68	1.9739	.6820	1.3461	.3883	.7665
69	1.9937	.6711	1.3380	.3810	.7596
0.70	2.0138	.6605	1.3301	.3738	.7528
71	2.0340	.6501	1.3223	.3668	.7461
72	2.0544	.6399	1.3147	.3599	.7394
73	2.0751	.6300	1.3072	.3532	.7329
74	2.0959	.6202	1.2998	.3467	.7266
75	2.1170	.6106	1.2926	.3403	.7204
76	2.1383	.6012	1.2855	.3341	.7144
77	2.1598	.5920	1.2785	.3280	.7084
78	2.1815	.5829	1.2716	.3221	.7027
79	2.2034	.5740	1.2649	.3163	.6969
0.80	2.2255	.5653	1.2582	.3106	.6912
81	2.2479	.5568	1.2517	.3050	.6856
82	2.2705	.5484	1.2452	.2996	.6802
83	2.2933	.5402	1.2389	.2943	.6749
84	2.3164	.5321	1.2326	.2891	.6697
85	2.3397	.5242	1.2265	.2840	.6644
86	2.3632	.5165	1.2205	.2790	.6593
87	2.3869	.5088	1.2145	.2742	.6545
88	2.4109	.5013	1.2086	.2694	.6495
89	2.4351	.4940	1.2029	.2647	.6446
0.90	2.4596	.4867	1.1972	.2602	.6400
91	2.4843	.4796	1.1916	.2557	.6352
92	2.5093	.4727	1.1860	.2513	.6306
93	2.5345	.4658	1.1806	.2470	.6260
94	2.5600	.4591	1.1752	.2429	.6218
95	2.5857	.4524	1.1699	.2387	.6172
96	2.6117	.4459	1.1647	.2347	.6130
97	2.6379	.4396	1.1595	.2308	.6088
98	2.6645	.4333	1.1544	.2269	.6046
99	2.6912	.4271	1.1494	.2231	.6004
1.00	2.7183	.4210	1.1445	.2194	.5964

times t_1 and t_2, if $t_1 t_2 = t_i^2$, is related by

$$s_2 = s_m - s_1 \tag{13}$$

This is obtained as follows: The relation

$$t_1 t_2 = t_i^2 \tag{14}$$

implies that

$$u_1 u_2 = u_i^2 = r^2/4B^2 \tag{15}$$

If one calculates s_1 from (1a), and s_2 from (1b), in which the equivalent of u_2 from (15) is substituted for u, then (13) is easily obtained.

In the part of the curve where it approaches asymptotically the maximum drawdown, or in the portion where $u \ll (r^2/4B^2)/u$ (which is obtained after a sufficiently long time has elapsed), the slope at any point may be approximated by

$$m \approx (2.3\ Q/4\pi T)e^{-q} \tag{16}$$

where

$$q = Tt/SB^2 \tag{16a}$$

and the drawdown by

$$s \approx s_m - (Q/4\pi T)W(q) \tag{17}$$

where $W(q)$ is the exponential integral $-E_i(-q)$ which is known as the 'well function' in groundwater hydrology.

The above two approximations are easily established by obtaining the asymptotic expressions of the righthand side of (5) and (1b) as u becomes very small.

From (16) and (17), the following relation is readily obtained

$$f(q) = e^q W(q) = 2.3\ (s_m - s)/m \tag{18}$$

Tables of functions—In order to apply the above theory in determining the formation constants, tables for the functions $e^x K_0(x)$, $e^x W(x)$, and $W(u, r/B)$ are necessary. The first two functions are constructed from already tabulated values of the component functions; their values, together with the values of the component functions, are given in Table 1. For values of the argument less than tabulated ($x < .01$), the functions may be approximated respectively by

$$e^x K_0(x) \approx K_0(x) \approx -2.3 \log_{10}(0.89x) \tag{19}$$

$$e^x W(x) \approx W(x) \approx -2.3 \log_{10}(1.78x) \tag{20}$$

The third function, or $W(u, r/B)$, is tabulated in Table 2. In constructing this table, use has been made of the reciprocal formula

$$\int_0^{(u\,r/2B)} (1/y) \exp\left[-y - r^2/4B^2y\right] dy = \int_{(r/2Bu)}^{\infty} (1/y) \exp\left(-y - r^2/4B^2y\right) dy$$

and of the Bessel function $W(v, r/B) = 2K_0(r/B)$. For $r/B > 0.1$, values of $W(u, r/B)$ for $(r/2B) \leq u \leq \infty$ were found by first calculating values of the integrand and then using numerical integration. Values of the function for $o < u \leq r/2B$ were then obtained by the reciprocal relation. For $r/B \leq 0.2$, values of the function for $o < u \leq r/2B$ were obtained from the series expansion [*Hantush* and *Jacob*, 1955, Eq. (13)] of the function, and the values for $u > r/2B$ from the reciprocal relation. It is probable that several of the tabulated values are in error by one unit in the fourth decimal, but very few may be in error by more than two units in the fourth decimal.

Application—Depending on the data collected from a pumping test, one of the following procedures may be followed in calculating the formation constants.

One observation well—If the period of the test is long enough so that the maximum drawdown can be extrapolated, the procedure is as follows: (1) Construct the time-drawdown curve from the observational data on semi-logarithmic paper (time in any convenient unit, being on the logarithmic scale). (2) Extrapolate the value of the maximum drawdown s_m. (3) Compute s_i from Eq. (9), or $s_i = (\frac{1}{2})s_m$. (4) The value s_i on the curve locates the inflection point. (5) Read the value t_i, or the time, at the inflection point. (6) Find the slope m_i of the curve at the inflection point. Usually this can be closely approximated by the slope of the straight portion of the curve on which the inflection point lies. (7) Substitute the information obtained in Steps (3) and (6) in Eq. (12) and interpolate for r/B from the Table of the function $e^{r/b}K_0(r/B)$ in Table 1. (8) Knowing r/B and r, calculate B. (9) Knowing Q, s_i, m_i, and r/B, calculate T from either Eq. (7) or (9). (10) Knowing T, t_i, r, and r/B, calculate S from Eq. (6). (11) Knowing T and B, calculate the 'leakance,' or the leakage coefficient K'/b', from the relation $K'/b' = T/B^2$.

Theoretically, when the calculated coefficients are used in conjunction with Eq. (1) and with assigned values of t, the calculated drawdowns should fall on the observed curve. This, however, usually is not true for the early portion of the observed curve, because generally the constants vary in the early stages of pumping. During the latter part of the test, or as time increases, the

TABLE 2 – *Values of the function* $= W(u, r/B) = \int_u^\infty (1/y)\, \exp\,(-y - r^2/4B^2y)\, dy$

u \ r/B	0	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.01
0	∞	14.0474	12.6611	11.8502	11.2748	10.8286	10.4640	10.1557	9.8887	9.6532	9.4425
.000001	13.2383	13.0031	12.4417	11.8153	11.2711	10.8283	10.4640	10.1557	9.8887		
.000002	12.5451	12.4240	12.1013	11.6716	11.2259	10.8174	10.4619	10.1554	9.8886	9.6532	
.000003	12.1397	12.0581	11.8322	11.5098	11.1462	10.7849	10.4509	10.1523	9.8879	9.6530	9.4425
.000004	11.8520	11.7905	11.6148	11.3597	11.0555	10.7374	10.4291	10.1436	9.8849	9.6521	9.4422
.000005	11.6289	11.5795	11.4384	11.2248	10.9642	10.6822	10.3993	10.1290	9.8786	9.6496	9.4413
.000006	11.4465	11.4053	11.2866	11.1040	10.8764	10.6240	10.3640	10.1094	9.8686	9.6450	9.4394
.000007	11.2924	11.2570	11.1545	10.9951	10.7933	10.5652	10.3255	10.0862	9.8555	9.6382	9.4361
.000008	11.1589	11.1279	11.0377	10.8962	10.7151	10.5072	10.2854	10.0602	9.8398	9.6292	9.4313
.000009	11.0411	11.0135	10.9330	10.8059	10.6416	10.4508	10.2446	10.0324	9.8219	9.6182	9.4251
.00001	10.9357	10.9109	10.8382	10.7228	10.5725	10.3963	10.2038	10.0034	9.8024	9.6059	9.4176
.00002	10.2426	10.2301	10.1932	10.1332	10.0522	9.9530	9.8386	9.7126	9.5781	9.4383	9.2961
.00003	9.8371	9.8288	9.8041	9.7635	9.7081	9.6392	9.5583	9.4671	9.3674	9.2611	9.1499
.00004	9.5495	9.5432	9.5246	9.4940	9.4520	9.3992	9.3366	9.2653	9.1863	9.1009	9.0102
.00005	9.3263	9.3213	9.3064	9.2818	9.2480	9.2052	9.1542	9.0957	9.0304	8.9591	8.8827
.00006	9.1440	9.1398	9.1274	9.1069	9.0785	9.0426	8.9996	8.9500	8.8943	8.8332	8.7673
.00007	8.9899	8.9863	8.9756	8.9580	8.9336	8.9027	8.8654	8.8224	8.7739	8.7204	8.6625
.00008	8.8563	8.8532	8.8439	8.8284	8.8070	8.7798	8.7470	8.7090	8.6661	8.6186	8.5669
.00009	8.7386	8.7358	8.7275	8.7138	8.6947	8.6703	8.6411	8.6071	8.5686	8.5258	8.4792
.0001	8.6332	8.6308	8.6233	8.6109	8.5937	8.5717	8.5453	8.5145	8.4796	8.4407	8.3983
.0002	7.9402	7.9390	7.9352	7.9290	7.9203	7.9092	7.8958	7.8800	7.8619	7.8416	7.8192
.0003	7.5348	7.5340	7.5315	7.5274	7.5216	7.5141	7.5051	7.4945	7.4823	7.4686	7.4534
.0004	7.2472	7.2466	7.2447	7.2416	7.2373	7.2317	7.2249	7.2169	7.2078	7.1974	7.1859
.0005	7.0242	7.0237	7.0222	7.0197	7.0163	7.0118	7.0063	6.9999	6.9926	6.9843	6.9750
.0006	6.8420	6.8416	6.8403	6.8383	6.8353	6.8316	6.8271	6.8218	6.8156	6.8086	6.8009
.0007	6.6879	6.6876	6.6865	6.6848	6.6823	6.6790	6.6752	6.6706	6.6653	6.6594	6.6527
.0008	6.5545	6.5542	6.5532	6.5517	6.5495	6.5467	6.5433	6.5393	6.5347	6.5295	6.5237
.0009	6.4368	6.4365	6.4357	6.4344	6.4324	6.4299	6.4269	6.4233	6.4192	6.4146	6.4094
.001	6.3315	6.3313	6.3305	6.3293	6.3276	6.3253	6.3226	6.3194	6.3157	6.3115	6.3069
.002	5.6394	5.6393	5.6389	5.6383	5.6374	5.6363	5.6350	5.6334	5.6315	5.6294	5.6271
.003	5.2349	5.2348	5.2346	5.2342	5.2336	5.2329	5.2320	5.2310	5.2297	5.2283	5.2267
.004	4.9482	4.9482	4.9480	4.9477	4.9472	4.9467	4.9460	4.9453	4.9443	4.9433	4.9421
.005	4.7261	4.7260	4.7259	4.7256	4.7253	4.7249	4.7244	4.7237	4.7230	4.7222	4.7212
.006	4.5448	4.5448	4.5447	4.5444	4.5441	4.5438	4.5433	4.5428	4.5422	4.5415	4.5407
.007	4.3916	4.3916	4.3915	4.3913	4.3910	4.3908	4.3904	4.3899	4.3894	4.3888	4.3882
.008	4.2591	4.2590	4.2590	4.2588	4.2586	4.2583	4.2580	4.2576	4.2572	4.2567	4.2561
.009	4.1423	4.1423	4.1422	4.1420	4.1418	4.1416	4.1413	4.1410	4.1406	4.1401	4.1396
.01	4.0379	4.0379	4.0378	4.0377	4.0375	4.0373	4.0371	4.0368	4.0364	4.0360	4.0356
.02	3.3547	3.3547	3.3547	3.3546	3.3545	3.3544	3.3543	3.3542	3.3540	3.3538	3.3536
.03	2.9591	2.9591	2.9591	2.9590	2.9590	2.9589	2.9589	2.9588	2.9587	2.9585	2.9584
.04	2.6813	2.6812	2.6812	2.6812	2.6812	2.6811	2.6810	2.6810	2.6809	2.6808	2.6807
.05	2.4679	2.4679	2.4679	2.4679	2.4678	2.4678	2.4678	2.4677	2.4676	2.4676	2.4675
.06	2.2953	2.2953	2.2953	2.2953	2.2952	2.2952	2.2952	2.2952	2.2951	2.2950	2.2950
.07	2.1508	2.1508	2.1508	2.1508	2.1508	2.1508	2.1507	2.1507	2.1507	2.1506	2.1506
.08	2.0269	2.0269	2.0269	2.0269	2.0269	2.0269	2.0269	2.0268	2.0268	2.0268	2.0267
.09	1.9187	1.9187	1.9187	1.9187	1.9187	1.9187	1.9187	1.9186	1.9186	1.9186	1.9185
.1	1.8229	1.8229	1.8229	1.8229	1.8229	1.8229	1.8229	1.8228	1.8228	1.8228	1.8227
.2	1.2227	1.2226	1.2226	1.2226	1.2226	1.2226	1.2226	1.2226	1.2226	1.2226	1.2226
.3	0.9057	0.9057	0.9057	0.9057	0.9057	0.9057	0.9057	0.9057	0.9056	0.9056	0.9056
.4	7024	7024	7024	7024	7024	7024	7024	7024	7024	7024	7024
.5	5598	5598	5598	5598	5598	5598	5598	5598	5598	5598	5598
.6	4544	4544	4544	4544	4544	4544	4544	4544	4544	4544	4544
.7	3738	3738	3738	3738	3738	3738	3738	3738	3738	3738	3738
.8	3106	3106	3106	3106	3106	3106	3106	3106	3106	3106	3106
.9	2602	2602	2602	2602	2602	2602	2602	2602	2602	2602	2602
1.0	0.2194	0.2194	0.2194	0.2194	0.2194	0.2194	0.2194	0.2194	0.2194	0.2194	0.2194
2.0	489	489	489	489	489	489	489	489	489	489	489
3.0	130	130	130	130	130	130	130	130	130	130	130
4.0	38	38	38	38	38	38	38	38	38	38	38
5.0	11	11	11	11	11	11	11	11	11	11	11
6.0	4	4	4	4	4	4	4	4	4	4	4
7.0	1	1	1	1	1	1	1	1	1	1	1
8.0	0	0	0	0	0	0	0	0	0	0	0

(Continued)

TABLE 2 – *Values of the function* $= W(u, r/B) = \int_u^\infty (1/y)\, exp\, (-y - r^2/4B^2y)\, dy$ *(continued)*

u \ r/B	0.01	0.015	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065	0.07	0.075	0.08	0.085	0.09	0.095	0.10
0	9.4425	8.6319	8.0569	7.6111	7.2471	6.9394	6.6731	6.4383	6.2285	6.0388	5.8658	5.7067	5.5596	5.4228	5.2950	5.1750	5.0620	4.9553	4.8541
.000001																			
.000002																			
.000003	9.4425																		
.000004	9.4422																		
.000005	9.4413																		
.000006	9.4394																		
.000007	9.4361	8.6319																	
.000008	9.4313	8.6318																	
.000009	9.4251	8.6316																	
.00001	9.4176	8.6313	8.0569																
.00002	9.2961	8.6152	8.0558	7.6111	7.2471														
.00003	9.1499	8.5757	8.0483	7.6101	7.2470														
.00004	9.0102	8.5168	8.0320	7.6069	7.2465	6.9394	6.6731												
.00005	8.8827	8.4533	8.0080	7.6000	7.2450	6.9391	6.6730												
.00006	8.7673	8.3880	7.9786	7.5894	7.2419	6.9384	6.6729	6.4383											
.00007	8.6625	8.3233	7.9456	7.5754	7.2371	6.9370	6.6726	6.4382	6.2285										
.00008	8.5669	8.2603	7.9105	7.5589	7.2305	6.9347	6.6719	6.4381	6.2284										
.00009	8.4792	8.1996	7.8743	7.5402	7.2222	6.9316	6.6709	6.4378	6.2283										
.0001	8.3983	8.1414	7.8375	7.5199	7.2122	6.9273	6.6693	6.4372	6.2282	6.0388	5.8658	5.7067	5.5596	5.4228	5.2950				
.0002	7.8192	7.6780	7.4972	7.2898	7.0685	6.8439	6.6242	6.4143	6.2173	6.0338	5.8637	5.7059	5.5593	5.4227	5.2949	5.1750	5.0620	4.9553	
.0003	7.4534	7.3562	7.2281	7.0759	6.9068	6.7276	6.5444	6.3623	6.1848	6.0145	5.8527	5.6999	5.5562	5.4212	5.2942	5.1747	5.0619	4.9552	4.8541
.0004	7.1859	7.1119	7.0128	6.8929	6.7567	6.6088	6.4538	6.2955	6.1373	5.9818	5.8309	5.6860	5.5476	5.4160	5.2912	5.1730	5.0610	4.9547	4.8539
.0005	6.9750	6.9152	6.8346	6.7357	6.6219	6.4964	6.3626	6.2236	6.0821	5.9406	5.8011	5.6648	5.5330	5.4062	5.2848	5.1689	5.0585	4.9532	4.8530
.0006	6.8009	6.7508	6.6828	6.5988	6.5011	6.3923	6.2748	6.1512	6.0239	5.8948	5.7658	5.6383	5.5134	5.3921	5.2749	5.1621	5.0539	4.9502	4.8510
.0007	6.6527	6.6096	6.5508	6.4777	6.3923	6.2962	6.1917	6.0807	5.9652	5.8468	5.7274	5.6081	5.4902	5.3745	5.2618	5.1526	5.0471	4.9454	4.8478
.0008	6.5237	6.4858	6.4340	6.3695	6.2935	6.2076	6.1136	6.0129	5.9073	5.7982	5.6873	5.5755	5.4642	5.3542	5.2461	5.1406	5.0381	4.9388	4.8430
.0009	6.4094	6.3757	6.3294	6.2716	6.2032	6.1256	6.0401	5.9481	5.8509	5.7500	5.6465	5.5416	5.4364	5.3317	5.2282	5.1266	5.0272	4.9306	4.8368

.001	6.3069	6.2765	6.2347	6.1823	6.1202	6.0494	5.9711	5.8864	5.7965	5.7026	5.6058	5.5071	5.4075	5.3078	5.2087	5.1109	5.0133	4.9208	4.8292
.002	5.6271	5.6118	5.5907	5.5638	5.5314	5.4939	5.4516	5.4047	5.3538	5.2991	5.2411	5.1803	5.1170	5.0517	4.9848	4.9166	4.8475	4.7778	4.7079
.003	5.2267	5.2166	5.2025	5.1845	5.1627	5.1373	5.1084	5.0762	5.0408	5.0025	4.9615	4.9180	4.8722	4.8243	4.7746	4.7234	4.6707	4.6169	4.5622
.004	4.9421	4.9345	4.9240	4.9105	4.8941	4.8749	4.8530	4.8286	4.8016	4.7722	4.7406	4.7068	4.6710	4.6335	4.5942	4.5533	4.5111	4.4676	4.4230
.005	4.7212	4.7152	4.7068	4.6960	4.6829	4.6675	4.6499	4.6302	4.6084	4.5846	4.5590	4.5314	4.5022	4.4713	4.4389	4.4050	4.3699	4.3335	4.2960
.006	4.5407	4.5357	4.5287	4.5197	4.5088	4.4960	4.4814	4.4649	4.4467	4.4267	4.4051	4.3819	4.3573	4.3311	4.3036	4.2747	4.2446	4.2134	4.1812
.007	4.3882	4.3839	4.3779	4.3702	4.3609	4.3500	4.3374	4.3233	4.3077	4.2905	4.2719	4.2518	4.2305	4.2078	4.1839	4.1588	4.1326	4.1053	4.0771
.008	4.2561	4.2524	4.2471	4.2404	4.2323	4.2228	4.2118	4.1994	4.1857	4.1707	4.1544	4.1368	4.1180	4.0980	4.0769	4.0547	4.0315	4.0073	3.9822
.009	4.1396	4.1363	4.1317	4.1258	4.1186	4.1101	4.1004	4.0894	4.0772	4.0638	4.0493	4.0336	4.0169	3.9991	3.9802	3.9603	3.9395	3.9178	3.8952
.01	4.0356	4.0326	4.0285	4.0231	4.0167	4.0091	4.0003	3.9905	3.9795	3.9675	3.9544	3.9403	3.9252	3.9091	3.8920	3.8741	3.8552	3.8356	3.8150
.02	3.3536	3.3521	3.3502	3.3476	3.3444	3.3408	3.3365	3.3317	3.3264	3.3205	3.3141	3.3071	3.2997	3.2917	3.2832	3.2742	3.2647	3.2547	3.2442
.03	2.9584	2.9575	2.9562	2.9545	2.9523	2.9501	2.9474	2.9444	2.9409	2.9370	2.9329	2.9284	2.9235	2.9183	2.9127	2.9069	2.9007	2.8941	2.8873
.04	2.6807	2.6800	2.6791	2.6779	2.6765	2.6747	2.6727	2.6705	2.6680	2.6652	2.6622	2.6589	2.6553	2.6515	2.6475	2.6432	2.6386	2.6338	2.6288
.05	2.4675	2.4670	2.4662	2.4653	2.4642	2.4628	2.4613	2.4595	2.4576	2.4554	2.4531	2.4505	2.4478	2.4448	2.4416	2.4383	2.4347	2.4310	2.4271
.06	2.2950	2.2945	2.2940	2.2932	2.2923	2.2912	2.2900	2.2885	2.2870	2.2852	2.2833	2.2812	2.2790	2.2766	2.2740	2.2713	2.2684	2.2654	2.2622
.07	2.1506	2.1502	2.1497	2.1491	2.1483	2.1474	2.1464	2.1452	2.1439	2.1424	2.1408	2.1391	2.1372	2.1352	2.1331	2.1308	2.1284	2.1258	2.1232
.08	2.0267	2.0264	2.0260	2.0255	2.0248	2.0240	2.0231	2.0221	2.0210	2.0198	2.0184	2.0169	2.0153	2.0136	2.0118	2.0099	2.0078	2.0056	2.0034
.09	1.9185	1.9183	1.9179	1.9174	1.9169	1.9162	1.9154	1.9146	1.9136	1.9125	1.9114	1.9101	1.9087	1.9072	1.9056	1.9040	1.9022	1.9003	1.8983
.1	1.8227	1.8225	1.8222	1.8218	1.8213	1.8207	1.8200	1.8193	1.8184	1.8175	1.8164	1.8153	1.8141	1.8128	1.8114	1.8099	1.8084	1.8067	1.8050
.2	1.2226	1.2225	1.2224	1.2222	1.2220	1.2218	1.2215	1.2212	1.2209	1.2205	1.2201	1.2196	1.2192	1.2186	1.2181	1.2175	1.2168	1.2162	1.2155
.3	0.9056	0.9056	0.9055	0.9054	0.9053	0.9052	0.9050	0.9049	0.9047	0.9045	0.9043	0.9040	0.9038	0.9035	0.9032	0.9029	0.9025	0.9022	0.9018
.4	7024	7023	7023	7022	7022	7021	7020	7019	7018	7016	7015	7014	7012	7010	7008	7006	7004	7002	7000
.5	5598	5597	5597	5597	5596	5596	5595	5594	5594	5593	5592	5591	5590	5588	5587	5586	5584	5583	5581
.6	4544	4544	4543	4543	4543	4542	4542	4542	4541	4540	4540	4539	4538	4537	4536	4535	4534	4533	4532
.7	3738	3738	3737	3737	3737	3737	3736	3736	3735	3735	3734	3734	3733	3733	3732	3732	3731	3730	3729
.8	3106	3106	3106	3106	3105	3105	3105	3105	3104	3104	3104	3103	3103	3102	3102	3101	3101	3100	3100
.9	2602	2602	2602	2602	2601	2601	2601	2601	2601	2600	2600	2600	2599	2599	2599	2598	2598	2597	2597
1.0	0.2194	0.2194	0.2194	0.2194	0.2193	0.2193	0.2193	0.2193	0.2193	0.2193	0.2192	0.2192	0.2192	0.2191	0.2191	0.2191	0.2191	0.2190	0.2190
2.0	489	489	489	489	489	489	489	489	489	489	489	489	489	489	489	489	489	488	488
3.0	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
4.0	38	38	38	38	38	38	38	38	38	38	38	38	38	38	38	38	38	38	38
5.0	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
6.0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
7.0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(Continued)

TABLE 2 – *Values of the function* $= W(u, r/B) = \int_u^\infty (1/y)\, exp\, (-y - r^2/4B^2y)\, dy$ *(continued)*

u \ r/B	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1.0
0	4.8541	4.0601	3.5054	3.0830	2.7449	2.4654	2.2291	2.0258	1.8488	1.6931	1.5550	1.4317	1.3210	1.2212	1.1307	1.0485	0.9735	0.9049	0.8420
.0001																			
.0002																			
.0003	4.8541																		
.0004	4.8539																		
.0005	4.8530																		
.0006	4.8510	4.0601																	
.0007	4.8478	4.0600																	
.0008	4.8430	4.0599																	
.0009	4.8368	4.0598																	
.001	4.8292	4.0595	3.5054																
.002	4.7079	4.0435	3.5043	3.0830	2.7449														
.003	4.5622	4.0092	3.4969	3.0821	2.7448														
.004	4.4230	3.9551	3.4806	3.0788	2.7444	2.4654	2.2291												
.005	4.2960	3.8821	3.4567	3.0719	2.7428	2.4651	2.2290												
.006	4.1812	3.8384	3.4274	3.0614	2.7398	2.4644	2.2289	2.0258											
.007	4.0771	3.7529	3.3947	3.0476	2.7350	2.4630	2.2286	2.0257											
.008	3.9822	3.6903	3.3598	3.0311	2.7284	2.4608	2.2279	2.0256	1.8488										
.009	3.8952	3.6302	3.3239	3.0126	2.7202	2.4576	2.2269	2.0253	1.8487										
.01	3.8150	3.5725	3.2875	2.9925	2.7104	2.4534	2.2253	2.0246	1.8486	1.6931	1.5550	1.4317	1.3210	1.2212	1.1307	1.0485			
.02	3.2442	3.1158	2.9521	2.7658	2.5688	2.3713	2.1809	2.0023	1.8379	1.6883	1.5530	1.4309	1.3207	1.2210	1.1306	1.0484	0.9735	0.9049	
.03	2.8673	2.8017	2.6896	2.5571	2.4110	2.2576	2.1031	1.9515	1.8062	1.6695	1.5423	1.4251	1.3177	1.2195	1.1299	1.0481	0.9733	0.9048	0.8420
.04	2.6288	2.5655	2.4816	2.3802	2.2661	2.1431	2.0155	1.8869	1.7603	1.6379	1.5213	1.4117	1.3094	1.2146	1.1270	1.0465	0.9724	0.9044	0.8418
.05	2.4271	2.3776	2.3110	2.2299	2.1371	2.0356	1.9283	1.8181	1.7075	1.5985	1.4927	1.3914	1.2955	1.2052	1.1210	1.0426	0.9700	0.9029	0.8409
.06	2.2622	2.2218	2.1673	2.1002	2.0227	1.9369	1.8452	1.7497	1.6524	1.5551	1.4593	1.3663	1.2770	1.1919	1.1116	1.0362	0.9657	0.9001	0.8391
.07	2.1232	2.0894	2.0435	1.9867	1.9206	1.8469	1.7673	1.6835	1.5973	1.5101	1.4232	1.3380	1.2551	1.1754	1.0993	1.0272	0.9593	0.8956	0.8360
.08	2.0034	1.9745	1.9351	1.8861	1.8290	1.7646	1.6947	1.6206	1.5436	1.4650	1.3860	1.3078	1.2310	1.1564	1.0847	1.0161	0.9510	0.8895	0.8316
.09	1.8983	1.8732	1.8389	1.7961	1.7460	1.6892	1.6272	1.5609	1.4918	1.4206	1.3486	1.2766	1.2054	1.1358	1.0682	1.0032	0.9411	0.8819	0.8259
.1	1.8050	1.7829	1.7527	1.7149	1.6704	1.6198	1.5644	1.5048	1.4422	1.3774	1.3115	1.2451	1.1791	1.1140	1.0505	0.9890	0.9297	0.8730	0.8190
.2	1.2155	1.2066	1.1944	1.1789	1.1602	1.1387	1.1145	1.0879	1.0592	1.0286	0.9964	0.9629	0.9284	0.8932	0.8575	8216	7857	7501	7148
.3	0.9018	0.8969	0.8902	0.8817	0.8713	0.8593	0.8457	0.8306	0.8142	0.7964	7775	7577	7369	7154	6932	6706	6476	6244	6010
.4	7000	6969	6927	6874	6809	6733	6647	6551	6446	6332	6209	6080	5943	5801	5653	5501	5345	5186	5024
.5	5581	5561	5532	5496	5453	5402	5344	5278	5206	5128	5044	4955	4860	4761	4658	4550	4440	4326	4210
.6	4532	4518	4498	4472	4441	4405	4364	4317	4266	4210	4150	4086	4018	3946	3871	3793	3712	3629	3543
.7	3729	3719	3704	3685	3663	3636	3606	3572	3534	3493	3449	3401	3351	3297	3242	3183	3123	3060	2996
.8	3100	3092	3081	3067	3050	3030	3008	2982	2953	2922	2889	2853	2815	2774	2732	2687	2641	2592	2543
.9	2597	2591	2583	2572	2559	2544	2527	2507	2485	2461	2436	2408	2378	2347	2314	2280	2244	2207	2168
1.0	0.2190	0.2186	0.2179	0.2171	0.2161	0.2149	0.2135	0.2120	0.2103	0.2085	0.2065	0.2043	0.2020	0.1995	0.1970	0.1943	0.1914	0.1885	0.1855
2.0	488	488	487	486	485	484	482	480	477	475	473	470	467	463	460	456	452	448	444
3.0	130	130	130	130	130	130	129	129	128	128	127	127	126	125	125	124	123	122	122
4.0	38	38	38	38	38	38	38	37	37	37	37	37	37	37	37	36	36	36	36
5.0	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11	11
6.0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
7.0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(Continued)

TABLE 2 – *Values of the function* $= W(u, r/B) = \int_u^\infty (1/y)\, exp\, (-y - r^2/4B^2y)\, dy$ (*concluded*)

u \ r/B	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	6.0	7.0	8.0	9.0
0	0.8420	0.4276	0.2278	0.1247	0.0695	0.0392	0.0223	0.0128	0.0074	0.0025	0.0008	0.0003	0.0001
.01													
.02													
.03	0.8420												
.04	8418												
.05	8409												
.06	8391												
.07	8360	0.4276											
.08	8316	4275											
.09	8259	4274											
.1	0.8190	0.4271	0.2278										
.2	7148	4135	2268	0.1247	0.0695								
.3	6010	3812	2211	1240	694								
.4	3026	3411	2096	1217	691	0.0392							
.5	4210	3007	1944	1174	681	390	0.0223						
.6	3543	2630	1774	1112	664	386	222	0.0128					
.7	2996	2292	1602	1040	639	379	221	127					
.8	2543	1994	1436	961	607	368	218	127	0.0074				
.9	2168	1734	1281	881	572	354	213	125	73				
1.0	0.1855	0.1509	0.1139	0.0803	0.0534	0.0338	0.0207	0.0123	0.0073	0.0025			
2.0	444	394	335	271	210	156	112	77	51	21	0.0008	0.0003	
3.0	122	112	100	86	71	57	45	34	25	12	6	2	
4.0	36	34	31	27	24	20	16	13	10	6	3	2	0.0001
5.0	11	10	10	9	8	7	6	5	4	2	1	1	0
6.0	4	3	3	3	3	2	2	2	2	1	1	0	
7.0	1	1	1	1	1	1	1	1	1	0	0		
8.0	0	0	0	0	0	0	0	0	0				

coefficients usually tend to attain their uniform values. Consequently, the latter part of the observation curve generally is more dependable in the analysis. Direct computation in Eq. (1) for drawdowns in the latter part of the test should compare fairly with observed values. Thus the next step is: (12) Use the coefficients calculated above for direct computation in Eq. (1) or (Table 2) for observed points on the straight portion of the observed curve and for points on the latter part of the curve. The calculated drawdowns should plot close to the curve in those portions.

Sometimes the extrapolated value of s_m is either over- or under-estimated, or/and the slope of the straight portion of the curve (which sometimes may be passed through the observation points in several ways) is drawn either flatter or steeper than necessary. In such cases the calculated drawdowns necessarily will deviate from the observed curve. The next step is to adjust the extrapolation of s_m, or the slope, or both, at the inflection point. The amount of adjustment is inferred from the amounts and direction of the deviations of the calculated values of drawdown from those observed. Then the above steps are repeated. With a little experience only one trial may be needed to arrive at a satisfactory answer.

Example—Figure 2 shows time-drawdown curve obtained from pumping test data carried out on the Moutrays farm in the Roswell artesian basin, New Mexico. The curve shown was obtained after the necessary adjustment for the general recovery of water levels that was observed to take place before and during the pumping test. Before starting the test, the well had been flowing at a small rate during a period of about 30 minutes. The constant drawdown observed in the well during that period was two feet, which was probably attained within the first 20 minutes after the well started flowing. A few minutes after starting the test, this observation well stopped flowing, and at the end of ten minutes after the start, the water level in the well had dropped an additional 2.15 ft. The observed drawdowns during the early part of the test (probably during the first 40 minutes after starting the test) were undoubtedly affected by the recovery of the water levels due to the cessation of the flow from the well. The curve shown in Figure 2 was not adjusted for this effect. Consequently, the early portion of the curve (probably within the first 40 minutes) does not represent the drawdown effected by the pumped well.

The discharge of the pumped well was 3.33 cfs,

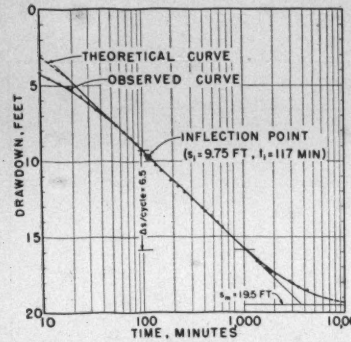

FIG. 2.– Time-drawdown curve for Moutrays farm drawdown pumping test, Roswell artesian basin, New Mexico

and its distance from the pumped well was 1060 ft.

From Figure 2, s_m is estimated as 19.5 ft. Thus $s_i = (\frac{1}{2})s_m = 9.75$ ft. The inflection point is then located on the curve by the point (9.75, 117), that is, $t_i = 117$ min. The slope of the straight portion of the curve on which the inflection point lies is measured as 6.5. Then from Eq. (12), $e^{r/B}K_0(r/B) = 2.3 \times 9.75/6.5 = 3.45$. For this value of the function, Table 1 gives $r/B = 0.041$ and $e^{r/B} = 1.042$. Hence $B = 1060/0.041 \approx 25800$ ft.; from Eq. (7), $T = 1.3 \times 3.33/4\pi \times 6.5 \times 1.042 = 0.09$ ft²/sec; the leakance, or $K'/b' = 0.09/25800^2 = 1.35 \times 10^{-10}$ sec.$^{-1}$; and from Eq. (6), $S = 0.0205 \times 4 \times 0.09 \times 117 \times 60/1060^2 = 0.000046$.

More than one observation well—If there is more than one well, the above procedure may be applied to each well independently, provided the maximum drawdown can be extrapolated for each of the wells observed. The coefficients obtained from the analysis of data from each well are then weighted to obtain their mean values in the vicinity of the well field.

The following method can be used, provided that at least two wells are observed and if the straight portion of the semi-logarithmic drawdown-time curves are fully developed. The procedure follows: (1) Construct the semi-logarithmic time-drawdown curves for all observation wells. (2) Find the values of the slope m_i of the straight portion of the curve for each well. (3) On semi-logarithmic paper plot distance versus slope (the slope being on the logarithmic scale), and construct the best-fit straight line through the plotted points. The equation of this straight line is given by Eq. (8) above. (4) Find the slope of this line, which is the change in r divided by the corresponding change in $\log_{10} m_i$. (5) Calculate B from the relation $B = 0.434(\Delta r/\Delta \log_{10} m_i)$. (6) Find the value of m_i when r is zero, designated by $(m_i)_0$. (7) Calculate T from the relation $T = 2.3\,Q/4\pi(m_i)_0$. (8) Knowing T and B, compute the leakance as in the previous method. (9) Knowing Q, r, T, and B, compute s_i in each observation well from Eq. (9).

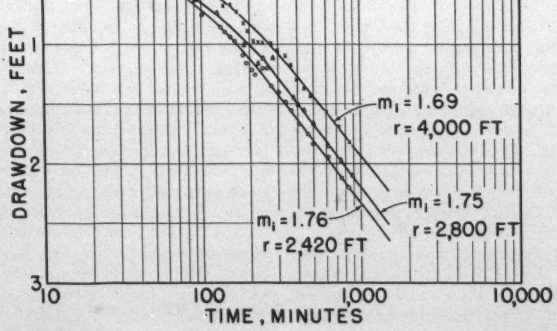

FIG. 3. –Time-drawdown curves for Wortman farm pumping test, Roswell artesian basin, New Mexico

(10) Knowing s_i in each well, locate the inflection point and read t_i. (11) Knowing T, r, r/B, and t_i for each well, calculate S by Eq. (6). (12) The mean of the values obtained in Step 11 is considered to be approximately the average storage coefficient in the well field.

Example — Semi-logarithmic time-drawdown curves for three observation wells constructed from data obtained from a pumping test carried out on the F. Wortman farm in the Orchard Park area of the Roswell artesian basin, New Mexico, are shown in Figure 3. The rate of discharge of the pumped well was 1.2 cfs. The distances r from the center of the pumped well to the three observation wells are 2420, 2800, and 4000 feet. From Figure 3, the approximate slopes m_i of the straight portions of the three curves are respectively 1.76, 1.75, and 1.69. Figure 4 shows the best-fit straight line through the points r, m_i plotted on semi-logarithmic paper. From Figure 4, $\Delta r/\Delta\log_{10} m_i \approx 78500$, and $(m_i)_0 = 1.9$. Thus, $B = 0.434 \times 78500 = 34100$ ft; $T = 2.3 \times 1.2/4\pi \times 1.9 = 0.116$ ft²/sec; and the leakance, $K'/b' = 0.116/34100^2 = 1 \times 10^{-10}$ sec^{-1}. The average value of S is computed as in Table 3.

When more than 50 pct of the maximum drawdown is developed in a few minutes of pumping—In certain cases, such as when the transmissibility and leakage coefficients are relatively very high, the maximum drawdowns caused by a pumping well are attained within a relatively short period of pumping. In such cases, leakage may affect the flow immediately, so that more than 50 pct of the maximum drawdown is developed within a few minutes after the beginning of pumping, in which case most of the points collected from a pumping test fall beyond the inflection point. Consequently, the time-drawdown curve forms that portion of the curve that approaches the maximum drawdown asymptotically. If a sufficient number of observation wells is not available to apply successfully the method based on steady distribution of drawdown, a method by which it is possible to obtain apparent values of the formation constants at any instant during pumping is outlined as follows: (1) Construct the semi-logarithmic time-drawdown curve from the observed data and estimate the maximum drawdown s_m. (2) On the plotted curve, choose any arbitrary point and note the coordinate values t and s. (3) Draw a tangent to the curve at the chosen point and measure the slope m of the tangent, which is equal to $\Delta s/\Delta\log_{10} t$. To construct a proper tangent may appear to be difficult, but with a little practice the difficulty is removed. (4) Knowing s_m, s, and m, compute the value of the function $f(q)$ from (18) and find the corresponding values of q, e^q, and $W(q)$ from Table 1. (5) Compute T from either (16) or (17). (6) Knowing T and s_m, compute $K_0(r/B)$ from Eq. (9) and find the corresponding value of (r/B) from Table 1 or Eq. (19). (7) Knowing r and r/B, compute the value of B. (8) Knowing T and B, compute the leakance K'/b' from the relation $K'/b' = T/B^2$. (9) Knowing t, T, B, and the value of q, compute S from Eq. (16a).

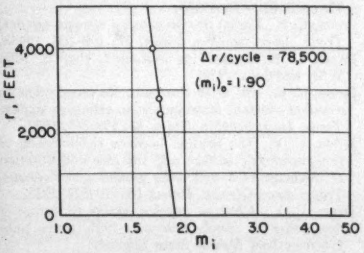

FIG. 4. – Distance-slope curve for Wortman farm pumping test, Roswell Artesian basin, New Mexico

TABLE 3 – *Computations for S as described in Steps 9–12 above*

Well	r	r/B	$K_0(r/B)$ from Table 1	s_i Eq. (9)	t_i from Fig. 3	S from Eq. (6)
	ft			ft	min	
1	2420	0.071	2.76	2.28	93	0.0000157
2	2800	0.082	2.623	2.16	95	0.0000138
3	4000	0.117	2.273	1.87	92	0.0000094
Average value of S						0.000013

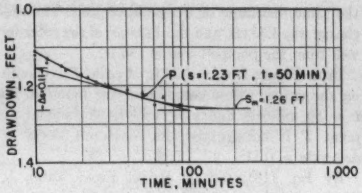

FIG. 5. – Time-drawdown curve for Berrendo pumping test, Roswell artesian basin, New Mexico

Example—Figure 5 shows the time-drawdown curve observed in the Berrendo recorder well in the Roswell artesian basin during two pumping tests carried out at different times for approximately

the same discharge of the pumped well. The discharge was 3.33 cfs, and the distance of the recorder well from the pumped well is 130 ft.

From Figure 5, $s_m = 1.26$ ft. A point P is chosen on the curve, whose coordinates are found to be $t = 50$ minutes and $s = 1.23$ ft. A tangent at point P is constructed; its measured slope = Δs/cycle = 0.11.

By Eq. (18), $f(q) = 0.626$. From Table 1, $W(q) = 0.247$, $e^q = 2.534$, and $q = 0.93$. Hence, by Eq. (16), $T = 2.3 \times 3.33/4\pi \times 0.11 \times 2.534 = 2.19$ ft²/sec; or by Eq. (17), $T = 3.33 \times 0.247/4\pi (1.26 - 1.23) = 2.18$ ft²/sec. By Eq. (9), $K_0(r/B) = 1.26 \times 2 \times \pi \times 2.19/3.33 = 5.2$. By Eq. (19), $r/B \approx 0.0061$. Then $B = 130/0.0061 = 21{,}300$ ft. The leakance is $K'/b' = 2.19/21300^2 = 4.82 \times 10^{-9}$ sec^{-1}. By Eq. (16a) $S = 4.82 \times 10^{-9} \times 50 \times 60/0.93 = 0.0000155$.

The aquifer which is penetrated by the wells on which the above mentioned pumping tests were made is composed almost entirely of limestone, anhydrite, and anhydritic limestone [*Theis*, 1942]. The effective porosity (specific yield) of the outcrop of this formation near the Hondo reservoir has been estimated as 0.05 [*Theis*, 1951]. The porosity of the formation in the artesian aquifer is probably smaller than that of the formation in areas near the Hondo reservoir where the solution process has been effective in the past.

The small values of the storage coefficient calculated from the pumping tests are expected, because the storage coefficient depends on, among other factors, the porosity and the compressibility efficient is given by *Jacob* [1950]

$$S = \theta\gamma b(\beta + \alpha/\theta)$$

where θ is the porosity of the aquifer (taken as 0.05 for the aquifer under discussion); γ is unit weight of the aquifer which characteristically is low for limestone aquifers.

The order of magnitude of the compressibility of the aquifer is obtained as follows: The storage co- of water (≈ 62 lb/ft³); b is the average thickness of the aquifer (taken as 100 ft); β is the compressibility of water (= 3.3×10^{-6} in²/lb); and α is the vertical compressibility of the aquifer.

The product $\theta\gamma b\beta$ gives the fraction of storage derived from expansion of water and the product $\gamma b\alpha$ gives the fraction derived from compression of the aquifer. Thus for the data indicated above, the fraction of the storage coefficient representing the storage derived from expansion of water is $0.05 \times 62 \times 100 \times 3.3 \times 10^{-6}/144 = 7.1 \times 10^{-6}$. If the storage coefficient is 1.55×10^{-5} (as obtained in the last example), then $\gamma b\alpha$ is 0.84×10^{-5} or $\alpha = 2 \times 10^{-7}$ in²/lb.

Acknowledgment—The author is indebted to C. R. Cassity of the New Mexico Institute of Mining and Technology for preparations of Tables 1 and 2, and to R. Crawford, field engineer of the Pecos Valley Conservancy District, for his help in making the pumping tests noted in the Roswell artesian basin.

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Some Observations in a Northwest Greenland Crevasse

JOHN C. COOK

Abstract—A crevasse believed to be of average size, located in the coastal belt of the northwest Greenland icecap, has been studied. In 1955, it was at least 300 m long and 15 m deep. At its widest point it was three meters broad, becoming narrower at the ends, top, and bottom. It was strongly bridged by snow, firn, glazing, and porous masses of vapor crystals. Ice shelves and wide cracks in the ceiling and floor which were observed may indicate at least three periods of widening, separated by one or more seasons of surface drift-bridging and bottom-water freezing. The bottom-water level depended upon an equilibrium between supply and drainage, which fluctuated with weather. No other changes were noted during two months of observations. Some interesting analogies between this crevasse and a natural limestone cave have been noted.

During a literature search made in preparation for some crevasse-detection studies, it became evident that very few detailed observations of crevasses had been made, particularly in polar regions. Therefore, in the course of subsequent experiments during the summer of 1955 on the icecap in northwest Greenland, a particular crevasse located near camp was studied at every opportunity over a period of two months.

Locale—This crevasse crossed the 1955 trail about 65 km east of the coast on Hayes Peninsula. It was located near the inner edge of the 'crevassed zone' which surrounds the central ice shield. Other crevasses of comparable size and orientation were known to exist four km west, and also 2.8 km and 11 km east of this one. Several large cracks, also essentially parallel to the crevasse, had been found in the general vicinity. One such crack, five to ten cm wide, only 100 m east of the crevasse, had been reported by probers.

The surface within a radius of two km of the crevasse sloped gently toward the west with a dip of 0.056 radian. The crevasse strike direction was 155° (south-southeast). Its elevation averaged 1020 m above sea level. According to seismic reflection and gravity studies [*Stanford Research Institute*, 1953, p. 113] the ice was 380 m thick. The bedrock also sloped westward, with a dip of 0.070 radian.

Size and shape—The crevasse was opened and entered at several points along a length of 300 m. A particularly accessible portion, 45 m long, was examined most carefully. There were indirect indications (for example, drainage) that the crevasse extended for at least one km, narrowing to a crack at each end. Its greatest width, three meters, occurred near the center, at a depth of from 350 to 500 cm from the 1955 surface.

Eight cross-sections of the crevasse are shown in Figure 1. The sections were obtained by a pair of roped-together climbers within the crevasse and an observer working on the surface above them, who communicated by means of portable radio transceivers. The surface observer (who wore skis for safety) thrust a marked bamboo measuring pole down through the snow bridge at measured intervals along the crevasse, locating it laterally on the internal axis of the crevasse by trial and error and by directions from the climber below. The ceiling thickness and other dimensions were read on the measuring pole or an auxiliary tape measure. The crevasse was entered by means of a rope ladder via the opening shown in Section 1, Figure 1, which had been made with high explosives.

The apparent axis of the crevasse was slightly crooked, wandering as much as a meter from a straight line at individual stations. At Section 7, a blank wall of 'snow' was encountered which may represent an offset. Probing indicated that the crevasse continues south from Section 7, after a westward displacement of two or three meters.

Examination of a list of the approximate dimensions of eight northwest Greenland crevasses which have been explored by probers attached to the Army Transportation Arctic Group indicated that this crevasse is representative of the list with respect to size. All these crevasses had been blasted open and filled with snow where they cross the trail, as indicated at Section 0 in Figure 1.

The snow bridge—Except for man-made markers, such as bamboo poles, there were no visible indications of this crevasse at the surface. Sagging or dropping of the snow bridge forming its roof had not occurred during the summer of 1955. In fact, the several wind-and-snow storms which occurred were seen to close up and smooth over any holes or irregularities which had been made. For example, a vertical crack 15 cm to 20 cm wide was discovered extending through the two meter-

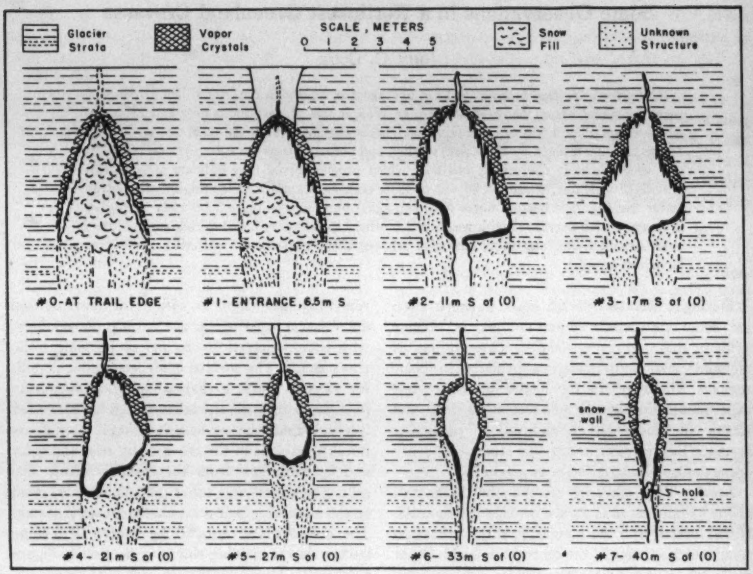

FIG. 1 – Cross sections in accessible portion of crevasse

thick roof of the crevasse throughout its accessible length, which presumably indicated a recent widening of the crevasse. This crack was bridged at the surface by five to 15 cm of firm snow. Those sections of the crack opened by probing became plugged and were fully healed at the surface by the first snowstorm thereafter.

It is surmised that a crevasse opening slowly, or in small steps, in a zone of accumulation, could become fully bridged by this process. As the initial crack grew wider over a period of months or years, successive layers of snow would be pulled apart, to be covered, in turn, by new layers. As a result, the crevasse ceiling should be shaped like a crude inverted V, as seen in section. The ceiling of the crevasse under discussion appeared to be amenable to such an interpretation. Figure 1 shows the original shape of this crevasse, as deduced on this basis, by dashed lines.

Shelves—At a depth of six meters, a platform of solid translucent ice was found which greatly facilitated exploration. This shelf between Sections 2 and 4 (looking south) is shown in Figure 2. Portions of the shelf extended from both sides of the crevasse throughout its accessible length. At Sections 4 and 5, a long, irregular mass of ice 70 to 90 cm higher than the shelf lay along the axis of the crevasse. This mass and the shelf were heavily and irregularly glazed with frozen drip-water from the ceiling and walls, as indicated by heavy solid lines in Figure 1.

Remnants of two other shelves projected from both walls at depths of 3.6 and 4.8 m below the surface. These remnants were heavily glazed and 'bearded' with icicles, which formed the heavy pulpit-like structures seen in Figure 2.

The icewater occupying the lower, narrow portion of the crevasse was observed to rise and fall with the weather. Several days of warm, melting weather (4°C at noon) early in July were followed by a rise of the water level to within ten cm of the big shelf (6.1 m below the surface). Three days of −2°C weather, on the other hand, were followed by a drop of water level to nine meters below the big shelf (15 meters below the surface). The same series of events was observed again in early August. In late August, the water level remained close to two meters below the big shelf despite ten days of freezing weather, and formed thin ice crusts at two separate levels.

These observations may be interpreted to mean that the big shelf in this crevasse probably originated from freezing of the bottom water at the six-meter level, when the crevasse was 60 cm narrower than in 1955. Subsequently, a further separation of the walls split the new ice, forming the present deep, 60 cm-wide crack. The irregular mass of ice lying between Stations 4 and 5 may have fallen subsequently from the roof.

The bottom water is obviously augmented by surface meltwater, which can be seen dripping from icicles on warm days. Slow draining away also occurs, via unknown channels. It is suggested that the crevasse connects via narrow cracks to porous surficial layers at a lower elevation, some distance to the northwest. There appears to be some resemblance to subsurface drainage in a karst (limestone) region.

Ice forms—The heavy glazing of floors by drip-water has been mentioned. Locally, 'stalagmite' knobs projected upward toward major icicles. Clusters of icicles up to one meter in length were prominent on the vaulted ceiling (see Fig. 2). Transparent 'flows' of glaze up to 15 cm thick were seen at several points. These are believed to represent the paths of unusual amounts of water seeping down from the surface.

'Vapor crystals' coated most of the ceiling and walls in masses 15 to 25 cm thick. Typical crystals were hollow hexagonal cylinders one cm high and

FIG. 2 – Icing at Sections 2 and 3

one cm wide, having walls one mm or less in thickness. The hexagon was often incomplete, in section resembling the letter G. Flat hexagonal plates growing on edge also were common. These fragile crystals grew in jumbled profusion, especially at Sections 6 and 7, where few icicles were found. Near the entrance hole (Section 1), their crisp forms became vague and blunted by melting during the course of the summer. Digging into the coating here and elsewhere revealed that the deeper portions of the crystal masses had become cemented into a strong, porous matrix, presumably by surface water seeping down from above. Many of the icicles were observed to grow from masses of vapor crystals on the ceiling of the crevasse. These excrescences had the combined effect of concealing the true form of the crevasse, but perhaps added some strength to the roof.

Air temperatures inside the crevasse were invariably lower than (daytime) air temperatures on the surface. A typical value was −4°C at the big shelf. There was little change with time.

The layered glacier strata were visible, with some difficulty, in the walls of this crevasse through the thick coatings of glaze. The strata seen were about ten cm thick, nearly transparent, and a pale blue in color. A hole chopped 30 cm into one wall at the six-meter level passed through a seven-cm coating of clear glaze and into bubbly glacier ice. This bubbly ice has been found at all depths from five cm to two meters in pits dug elsewhere in the vicinity of this crevasse. It was clear, except for scattered, irregular bubbles which presumably arose from entrapped air as the parent snow was compacted. These bubbles ranged from one to five mm in greatest dimension, and commonly possessed several cusps or points. Various layers of this ice contained from one to 20 bubbles per cubic centimeter.

Acoustics—The voices of persons at distances up to 15 m were easily heard in this crevasse. Beyond that distance, there was some difficulty in conversing. The crevasse produced very little reverberation; that is, it was acoustically 'dead,' probably because of the multitude of icicles and hollow crystals, and its extremely irregular shape. Subjectively, the interior of this crevasse sounded like a small limestone cave, being both 'dead' and extremely quiet except for dripping water.

Shouts within the crevasse could be heard at the surface only by pressing an ear to the snow over the thinnest part of the bridge (except near the entrance hole). However, conversations were possible through a five cm hole punched through the roof.

Bearing strength—On July 9, following three days of cold weather (−2°C), a modified type M29C 'weasel' was driven (inadvertently) across the widest portions of the crevasse, in five places. This weasel was a fully-tracked vehicle weighing about 2300 kg. Its weight rested on two tread areas each 38 cm by 200 cm in dimensions, 115 cm apart center to center. The crusted snow surface buckled downward six cm while the weasel was crossing over Section 4. During the remainder of July and August, several hundred crossings were made between Sections 5 and 6 without signs of subsidence. This portion of the crevasse was too narrow to admit a vehicle and, therefore, was considered safe for weasel traffic.

Men on foot, roped together or carrying safety poles spanning the crevasse, walked over all parts of the roof of this crevasse in cold weather. Mishaps generally occurred only when the air temperature was well above freezing (+2°C); on several occasions men broke through the bridge with one foot, at times sinking in above the knee. However, there were no injuries and breakthrough was relatively uncommon.

These incidents, together with observations made while probing the bridge with bamboo poles, indicated that the bridge had a complex structure; strong near-surface layers (wind-crusts?) were separated from each other and from the strong ceiling coatings beneath by soft spots or voids. The 20-cm ceiling crack and other weak points can be seen from within the crevasse as luminous areas transmitting a pale blue component of sunlight through the ceiling.

Thanks are due Robert Burns and Clark Sonntag of the First (Army) Engineers Arctic Task Force, who assisted the author in gathering data, to J. J. Wormser of Southwest Research Institute for Figure 2, and to the Defense Department for permission to publish this description.

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Frequency of Discharges From Ungaged Catchments

J. E. Nash

Abstract—A method is presented by which the frequency of discharges from ungaged catchments can be related to the rainfall frequency and the unit hydrograph for the catchment. The application of the method to well drained catchments in Ireland is demonstrated.

Introduction—A method sometimes used to calculate the frequencies of discharges from an ungaged catchment, being given the unit hydrograph and the rainfall frequency data, is to assume that the frequency of any given discharge is the frequency of the amount of rainfall required, in a certain critical period, to produce the given discharge. In the notation defined below, this assumption may be stated as

$$F_q = F\left[\frac{q}{U(T_c, P)P}, T_c \text{ or less}, A\right] \quad (1)$$

where T_c is the critical period for the catchment. The critical period may have a physical meaning, as the time of concentration of the catchment, or it may be defined as the value of T which makes

$$F\left[\frac{q}{U(T, P)P}, T \text{ or less}, A\right]$$

a maximum. The author suggests that, even when T_c is given the latter definition, Eq. (1) underestimates F_q for the following reasons: (1) The frequencies of storms of duration greater than T_c, which produce q but which contain no period T_c of sufficient rainfall to produce q are neglected. (2) For storms of duration less than T_c the peak of the unit hydrograph is greater than the peak of the unit hydrograph of period T_c. Consequently, in such cases, q can be produced by storms of lesser amount than $q/U(T_c, P)P$

The principle presented in this paper is that the frequency of q can be obtained by adding the frequencies of all storms which produce q. That is, the frequency of q is the sum of the frequency of the amount of rainfall required to produce q, in a storm of duration one hour or less, plus the frequency of the amount of rainfall required to produce q in a storm of duration between one and two hours, plus the frequency of the amount of rainfall required to produce q in a storm of duration two to three hours, etc.

Notation—The following notation is used.

A the catchment area, sq mi

S the catchment slope, in parts per 10,000

R the amount or rainfall, inches

T the duration of rainfall, hours

h an arbitrary short period

M the mean annual rainfall, inches

P the proportion of the total rainfall which becomes effective

Q the peak discharge, ft³/sec

q the peak discharge per square mile, ft³/sec

F_Q the frequency of Q, occurrences per year

F_q the frequency of q, occurrences per year

$F(R, T \text{ or less}, A)$ the frequency with which a rainfall amount R inches in a period T hours or less, on a catchment of area A is equalled or exceeded

$F(R, T \text{ or less}, 0)$ the frequency with which a rainfall amount R inches in a period T hours or less, at a single gage, is equalled or exceeded

$F(R, T, A)$ the frequency with which a rainfall amount R inches in a period of duration between $T \pm h$ on a catchment of area A is equalled or exceeded

$F(R, T, 0)$ the frequency with which a rainfall amount R inches in a period of duration between $T \pm h$, at a single gage, is equalled or exceeded

$\mu(T, A)$ a function of duration and area, giving the ratio of the frequency of any amount in a period of duration between $T \pm h$ on a catchment of area A to the frequency of the same amount in the same period at a single gage, that is

$$\mu(T, A) = \frac{F(R, T, A)}{F(R, T, 0)}$$

$U(T, t)$ the ordinate at time t, of the unit hydrograph of period T, ft³/sec. per square mile for one inch of effective rainfall

$U(T, P)$ The peak of the unit hydrograph of period T

$U(0, t)$ the ordinate at time t, of the instantaneous unit hydrograph

$U(0, P)$ the peak of the instantaneous unit hydrograph

V the area of the unit hydrograph; that is 1 inch × 1 square mile = 645 ft³ hr/sec

y the ordinate of the dimensionless unit hydrograph = $U(0, t)/U(0, P)$

x the abscissa of the dimensionless unit hydrograph = $tU(0, P)/V$

S_t the ordinate, at time t, of the S curve

Assumptions—(1) On a given catchment P is constant. This assumption is not in accordance with the infiltration theory but it is a simplification usually found necessary in developing runoff formulas. It does not create any theoretical difficulty, as on a completely impervious catchment, where the runoff is always 100 pct, the assumption is exact.

(2) On a given catchment, a rainfall amount R in a period of duration between $T \pm h$ causes a peak discharge q, which is proportional to R and is a function of T in accordance with the unit hydrograph theory; that is

$$q = PRU(T, P) \tag{2}$$

This assumption contains a possibly serious source of error which may be demonstrated as follows; Figure 1 shows a non uniform rain storm in which the amount of rainfall R_1, in the period T_1, is such as causes q in accordance with Eq. (2). Similarly the amount R_2 in the period T_2 is sufficient to cause q. In accordance with our assumption, we take this storm as causing two peak discharges of q, whereas in fact one peak discharge greater than q occurs.

(3) On a given catchment the frequency of q is the sum of the frequencies of all storms which cause q; that is

$$F_q = \Sigma F(R, T, A) \qquad \text{for } T = 0, 2h, 4h, 6h \cdots \tag{3}$$

where $R = q/U(T, P)P$

(4) That we have an equation, $F(R, T$ or less, $A)$ applicable to the region in which the catchment lies, giving the frequency of rainfall amounts on a catchment of area A in a given period or less as a function of the area and period. While in most regions, data are available relating amount-duration-frequency for rainfall at single gages, there is a great scarcity of information on the manner in which the frequency of a given amount in a given period diminishes as the area over which the amount is measured increases.

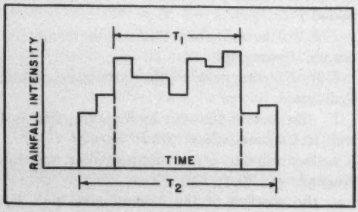

FIG. 1 – Non uniform rainfall

In the general theory below, two formulas are assumed, the first, $F(R, T$ or less, $0)$, giving the frequency of an amount R in period T or less, at a single gage, the second $\mu(T, A)$ giving the ratio of the frequency of any amount, in a period of duration between $T \pm h$ on a catchment of area A, to the frequency of the same amount in the same period at a single gage; that is

$$\mu(T, A) = \frac{F(R, T, A)}{F(R, T, 0)} \tag{4}$$

The general theory—

$$F(R, T, 0) = F(R, \overline{T + h} \text{ or less}, 0) - F(R, \overline{T - h} \text{ or less}, 0) \tag{5}$$

for all values of T not less than h

By Assumption 3.

$$F_q = \Sigma F\left[\frac{q}{PU(T, P)}, T, A\right] \qquad \text{for } T = 0, 2h, 4h, 6h \text{ etc.}$$

$$= \mu(0, A)F\left[\frac{q}{PU(0, P)}, h \text{ or less}, 0\right] + \Sigma \mu(T, A)F\left[\frac{q}{PU(T, P)}, T, 0\right] \tag{6}$$

for $T = 2h, 4h, 6h$ etc., which by (5) becomes

$$F_q = \mu(0, A)F\left(\frac{q}{PU(0, P)}, h \text{ or less}, 0\right) + \Sigma \mu(T, A)\left\{F\left(\frac{q}{PU(T, P)}, \overline{T + h} \text{ or less}, 0\right) - F\left(\frac{q}{PU(T, P)}, \overline{T - h} \text{ or less}, 0\right)\right\} \tag{7}$$

for $T = 2h, 4h, 6h \cdots$

This equation is general and can be made applicable to any region by inserting the local expressions for $F(R, T$ or less, $0)$, $\mu(T, A)$, $U(0, P)$ and $U(T, P)$. Normally, one would express $U(T, P)$ as a function of $U(0, P)$ and T.

The application of equation 7 to well drained catchments in Ireland—For $F(R, T$ or less, $0)$, the most suitable rainfall data, available in Ireland, are *Dillon's* [1954] analysis of a 35 years record of a continuous recording rain gage at Cork. Dillon's analysis gives $F(R, T$ or less, $0) = CT^2/R^5$ where C is a constant having the value 0.036 at Cork. The author uses Dillon's formula for the whole of Ireland, adjusting C in proportion the fifth power

of the mean annual rainfall in the region in which the catchment lies. Thus the formula becomes

$$F(R, T \text{ or less}, 0) = 0.036(M/40)^{5}T^{2}/R^{5} \quad (8)$$

where M is the mean annual rainfall in inches (= 40 at Cork).

For $\mu(T, A)$, as far as the author is aware, no data are available in Ireland relating the frequencies of equal rainfall amounts on different areas. However, the late George *Bramsby-Williams* [1952] prepared a set of curves for the British Isles, showing the amounts of rainfall in various periods to be expected with equal frequency on catchments of various areas. Figure 2 was obtained from these curves. It is plotted on logarithmic-probability paper to obtain greater accuracy in reading higher values of μ.

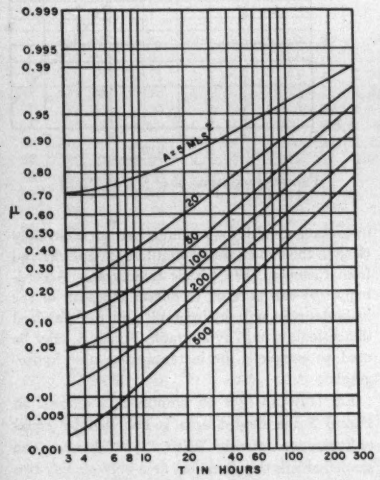

FIG. 2 – Variation of mean rainfall intensity with area and duration

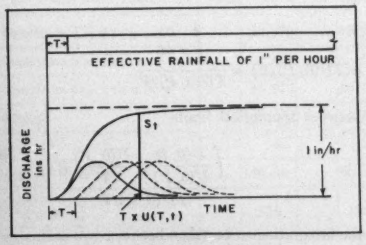

FIG. 3 – Obtaining the S curve from a known unit hydrograph

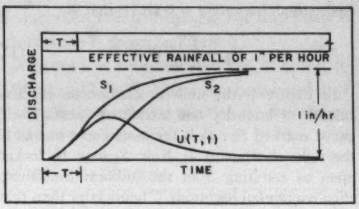

FIG. 4 – Obtaining a unit hydrograph of any period from a known S curve

For $U(0, P)$, a correlation, between the instantaneous unit hydrograph and the catchment characteristics, has been obtained by the staff of the Office of Public Works, Ireland. This correlation, which is applicable only to catchments containing no large lakes or flooded areas gives

$$U(0, P) = 4.17A^{-0.35}S^{0.6825} \quad (9)$$

where S is obtained by imposing a grid on a map of the catchment and taking the median value of the maximum slope occurring at the intersections of the grid. The coefficient of correlation for the nine points used in the correlation was 0.75.

For $U(T, P)$, the relation between $U(T, P)$ and $U(0, P)$ is a function of the shape of the instantaneous unit hydrograph. In Figure 3 the uniform continuous effective rainfall of intensity one inch per hour, causes the hydrograph (S curve) to rise as shown and approach a value equal to the intensity of the effective rainfall asymptotically. The amount of effective rainfall in the first period T is T inches and hence the discharge, at time t, due to this rainfall, is $TU(T, t)$. Similarly the discharge, at time t, due to the second rainfall period, is $TU(T, t - T)$ and the discharge at time t, due to the third rainfall period, is $TU(T, t - 2T)$, etc.

Now S_t, the ordinate of the S curve at time t, equals the sum of the discharges, at time t, due to each rainfall period; that is

$$S_t = T[U(T, t) + U(T, t - T) + U(T, t - 2T), \text{etc.},] \quad (10)$$

As T, the period of the unit hydrograph, is diminished indefinitely, the right-hand side of (10) approaches the area of the instantaneous unit

hydrograph between $t = 0$ and t; that is

$$S_t = \int_0^t U(0, t)\, dt \tag{11}$$

In Figure 4, the uniform continuous effective rainfall of intensity one inch/hour causes the S curve marked S_1. S_2 is the same curve moved to the right on amount T. Now S_2 may be looked upon as resulting from the uniform continuous effective rainfall beginning T hours later than that which produced S_1. The difference between the two S curves must be due to the effective rainfall from 0 to T. The volume of this effective rainfall is T inches. Therefore the unit hydrograph of period T is the difference between the two S curves divided by T.

$$\begin{aligned} U(T, t) &= (1/T)(S_t - S_{t-T}) \\ &= (1/T)\left[\int_0^t U(0, t)dt - \int_0^{t-T} U(0, t)\, dt\right] \\ &= (1/T)\int_{t-T}^{t} U(0, t)\, dt \end{aligned} \tag{12}$$

That is, the ordinate at time t of the unit hydrograph of period T is the mean ordinate of the instantaneous unit hydrograph between t and $t - T$. In particular, the peak of the unit hydrograph of period T is the mean ordinate of the instantaneous unit hydrograph between t and $t - T$, where t is chosen to obtain the maximum value of the integral.

In certain cases, (12) can be simplified further. The curve obtained by dividing the ordinates of an instantaneous unit hydrograph by the peak and multiplying the abscissae by the peak divided by the area of the instantaneous unit hydrograph is known as the dimensionless unit hydrograph. It expresses $Y = U(0, t)/U(0, P)$ as a function of $X = tU(0, P)/V$. In the correlation of the unit hydrographs with the catchment characteristics, referred to above, it was found that the dimensionless unit hydrographs derived from the several

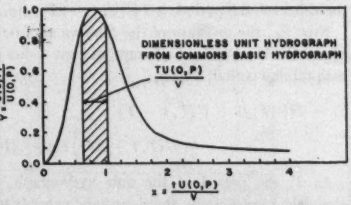

FIG. 5 – Dimensionless unit hydrograph, from Commons basic hydrograph

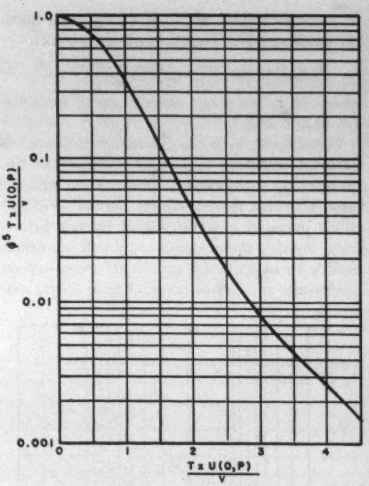

FIG. 6 – Evaluation of $\phi^5\,[TU(0, P)/V]$

instantaneous unit hydrographs were all reasonably close to the dimensionless unit hydrograph derived from *Commons* [1942] basic hydrograph. Accordingly, (9) can be used to obtain the peak of the instantaneous unit hydrograph and the standard dimensionless unit hydrograph, Figure 5, may be used to complete the instantaneous unit hydrograph.

Eq. (12) can now be simplified as follows. In Figure 5 the shaded area is bounded by equal ordinates separated by $TU(0, P)/V$. Therefore the shaded area is the maximum area between any two ordinates separated by this amount. The mean ordinate of this area is a function of $TU(0, P)/V$, say

$$\varphi(TU(0, P)/V) = \frac{\int y\, dx}{TU(0, P)/V}$$

between appropriate limits

$$= \frac{\int \frac{U(0, t)}{U(0, P)} \times \frac{U(0, P)}{V}\, dt}{TU(0, P)/V}$$

the integration to be taken between two ordinates separated by T and chosen in position so as to obtain the maximum value of the integral.

$$\therefore \varphi(TU(0,P)/V) = -\frac{1}{U(0,P)} \int \frac{U(0,t)}{T}\, dt = \frac{U(T,P)}{U(0,P)}$$

or

$$U(T,P) = U(0,P)\varphi[TU(0,P)/V] \quad (13)$$

$\varphi(TU(0,P)/V)$ is very easily calculated from the dimensionless unit hydrograph. The fifth power of this function is shown in Figure 6.

We have now expressions for $F(R, T \text{ or less}, 0)$, $U(T,P)$ and $U(0,P)$. These may be inserted in (7) to obtain the particular solution for well-drained catchments in Ireland.

TABLE 1—*Evaluation of Eq. 15 for* $U(O,P) = 100$ *ft³/sec*

n	$\frac{50n}{V}$	φ^5	$n\varphi^5$	$U(O,P) = 100$													
				$T = \frac{50n}{U(O,P)}$	A = 5 sq mi		A = 20 sq mi		A = 50 sq mi		A = 100 sq mi		A = 200 sq mi		A = 500 sq mi	
					u	$n\varphi^5 u$	u	$n\varphi^5 u$	u	$n\varphi^5 u$	u	$n\varphi^5 u$	u	$n\varphi^5 u$	u	$n\varphi^5 u$
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
2	.155	.97	1.94	1	.68	1.319	.20	.388	.10	.194	.045	.087	.013	.025	.001	.002
4	.310	.90	3.60	2	.69	2.484	.205	.738	.107	.385	.045	.162	.014	.050	.0015	.005
6	.465	.79	4.74	3	.695	3.294	.22	1.043	.115	.545	.045	.213	.015	.071	.002	.009
8	.620	.66	5.28	4	.71	3.749	.25	1.320	.120	.634	.050	.264	.019	.100	.003	.016
10	.775	.53	5.30	5	.72	3.816	.28	1.484	.137	.726	.062	.329	.025	.132	.0045	.024
12	.930	.40	4.80	6	.73	3.504	.305	1.464	.155	.744	.075	.360	.030	.144	.006	.029
14	1.085	.30	4.20	7	.74	3.108	.34	1.428	.175	.735	.085	.357	.035	.147	.008	.034
16	1.240	.218	3.49	8	.75	2.618	.37	1.292	.200	.698	.100	.349	.045	.157	.011	.038
18	1.395	.155	2.79	9	.76	2.120	.40	1.116	.215	.600	.115	.321	.050	.140	.0135	.038
20	1.550	.110	2.20	10	.77	1.694	.42	.924	.23	.506	.125	.275	.060	.132	.017	.037
22	1.705	.079	1.74	11	.775	1.349	.445	.774	.25	.435	.140	.244	.065	.113	.020	.035
24	1.860	.057	1.37	12	.785	1.075	.465	.637	.265	.363	.155	.212	.075	.103	.025	.034
26	2.015	.042	1.09	13	.795	.867	.485	.529	.28	.305	.17	.185	.085	.093	.030	.033
28	2.170	.0315	.882	14	.805	.710	.505	.445	.300	.265	.185	.163	.095	.084	.033	.029
30	2.325	.0235	.705	15	.815	.575	.53	.374	.31	.219	.20	.141	.10	.071	.038	.027
32	2.480	.0177	.566	16	.820	.464	.55	.311	.33	.187	.21	.119	.11	.062	.042	.024
34	2.636	.0135	.459	17	.830	.381	.56	.257	.345	.158	.22	.101	.12	.055	.047	.022
36	2.791	.0107	.385	18	.835	.321	.58	.223	.355	.137	.23	.088	.13	.050	.052	.020
38	2.946	.0086	.327	19	.840	.275	.59	.193	.37	.121	.25	.082	.135	.044	.057	.019
40	3.101	.0070	.280	20	.845	.237	.60	.168	.38	.106	.26	.073	.14	.039	.060	.017
42	3.256	.0059	.248	21	.850	.211	.61	.151	.39	.097	.27	.067	.15	.037	.065	.016
44	3.411	.0050	.220	22	.855	.188	.62	.136	.405	.089	.28	.060	.16	.035	.070	.015
46	3.566	.00425	.196	23	.860	.169	.63	.123	.42	.082	.29	.056	.165	.032	.075	.015
48	3.721	.0036	.173	24	.862	.149	.645	.112	.43	.074	.30	.051	.175	.030	.080	.014
50	3.876	.0030	.150	25	.867	.130	.655	.098	.445	.067	.31	.046	.185	.028	.085	.013
52	4.031	.0026	.135	26	.871	.118	.665	.090	.46	.062	.32	.043	.195	.026	.090	.012
54	4.186	.0022	.119	27	.875	.104	.675	.080	.47	.056	.33	.039	.205	.024	.095	.011
56	4.341	.0019	.106	28	.880	.093	.685	.073	.485	.051	.34	.036	.21	.022	.100	.011
58	4.496	.0016	.093	29	.882	.082	.69	.064	.495	.046	.35	.032	.22	.020	.110	.010
60	4.651	.0014	.084	30	.885	.074	.70	.059	.51	.043	.36	.030	.23	.019	.115	.010
Sum from $n = 2$ to $n = 60$					...	35.278	...	16.094	...	8.730	...	4.585	...	2.085	...	.619
Sum from $n = 62$ to $n = \infty$					...	.637	...	.558	...	.445	...	.361	...	.269	...	.184
Sum from $n = 2$ to $n = \infty$					...	35.915		16.652		9.175		4.946		2.354		.803
$4\Sigma n\mu\varphi^5$					...	143.66	...	66.608	...	36.700	...	19.784	...	9.416	...	3.212
$\mu(O, A)$					...	.68	...	.20	...	.10	...	.045	...	.013	...	.002
$\mu(O, A) + 4\Sigma n\mu\varphi^5$					...	144.34	...	66.808	...	36.800	...	19.829	...	9.429	...	3.214
$\frac{QFQ^{0.2}}{P} \times \frac{40}{M}$					...	526	...	1800	...	4000	...	7080	...	12200	...	24.600
Catchment slope					...	260	...	450	...	650	...	850	...	1100	...	1600

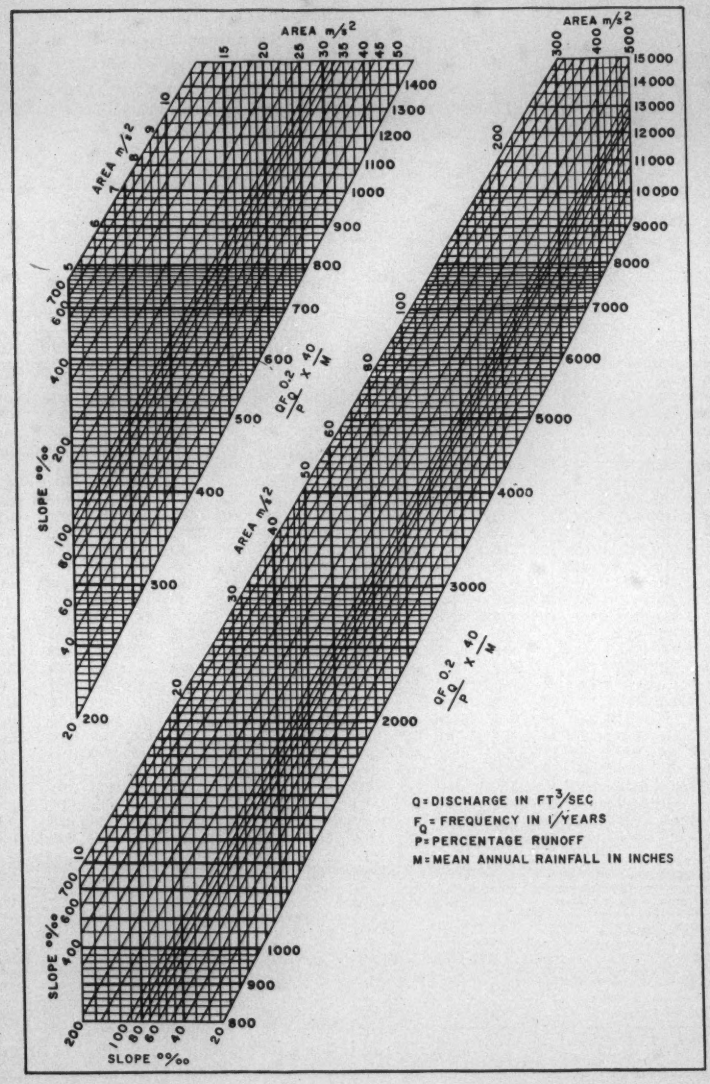
AREA m/s²
SLOPE °/₀₀
$\frac{QF_Q 0.2}{P} \times \frac{40}{M}$
Q = DISCHARGE IN FT³/SEC
F_Q = FREQUENCY IN 1/YEARS
P = PERCENTAGE RUNOFF
M = MEAN ANNUAL RAINFALL IN INCHES

FIG. 7 – The frequencies of discharges from well drained catchments in Ireland

$$F_q = \mu(0, A)(0.036)\left(\frac{M}{40}\right)^5 h^2 \frac{P^5U^5(0, P)}{q^5}$$

$$+ \Sigma\mu(T, A)\left[0.036\left(\frac{M}{40}\right)^5 (T+h)^2 \frac{P^5U^5(T, P)}{q^5}\right.$$

$$\left. - 0.036\left(\frac{M}{40}\right)^5 (T-h)^2 \frac{P^5U^5(T, P)}{q^5}\right]$$

for $T = 2h, 4h, 6h$, etc.

$$= 0.036 \frac{P^5U^5(0, P)}{q^5}\left(\frac{M}{40}\right)^5$$

$$\cdot[h^2\mu(0, A) + \Sigma\mu(T, A)\, 4Th\varphi^5(TU(0, P)/V)] \quad (14)$$

for $T = 2h, 4h, 6h$, etc. As h is arbitrary, provided it is small, we may take $h = 50$ ft^3 hr sec^{-1}/$U(0, P)$ (taking h as being inversely proportional to $U(0, P)$ simplifies the subsequent calculations). We shall also define n by the equation $T = nh$. Hence $T = 50n/U(0, P)$ and $TU(0, P)/V = 50n/V$

Substituting for T and h in (14)

$$F_q = 0.036 \frac{P^5U^5(0, P)}{q^5}\left(\frac{M}{40}\right)^5$$

$$\left\{\mu(0, A)\left[\frac{50}{U(0, P)}\right]^2 + 4\Sigma\mu(T, A)n\right.$$

$$\left.\left[\frac{50}{U(0, P)}\right]^2 \varphi^5\left(\frac{50n}{V}\right)\right\}$$

for $h = 2, 4, 6$ etc., or

$$\frac{Q^5F_q}{P^5} \times \left(\frac{40}{M}\right)^5 = 0.036A^5(50)^2U^3(0, P)$$

$$\left[\mu(0, A) + 4\Sigma\mu(T, A)n\varphi^5\left(\frac{50n}{V}\right)\right] \quad (15)$$

for $n = 2, 4, 6$ etc. The right hand side of this equation is a function of catchment slope and area. Table 1 shows the evaluation of this factor for catchments of various areas having $U(0, P) = 100$ ft^3/sec. Column 3 is obtained from Figure 6. Column 6 is obtained from Figure 2; columns 7, 9, 11, 13, 15 and 17 give the values of the elements within the Σ sign in (15) for $n = 2, 4, 6, 8$, etc. These columns are totaled and an approximation made to the sum of the remaining terms to infinity by assuming that the remaining terms form a geometric progression whose common ratio is the fourth root of the ratio of the 60th term to the 56th term. The catchment slope corresponding to $U(0, P) = 100$ ft^3/sec and $A = 5, 20, 50, 100, 200$, and 500 sq mi respectively is obtained from (9). Similar calculations were made for other values of $U(0, P)$ and when the final result was plotted on logarithmic paper, it was found that the data could be represented by a series of straight lines, one for each value of S, Figure 7. The portion of the diagram in the top left hand corner is an extension of the main portion downwards and to the left.

In this chart, as in the general theory, no allowance has been made for ground water. Where this is significant, an addition of one to two cubic feet per second per square mile should be made.

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An Investigation of the Solitary Wave*

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Abstract—Two solutions are presented to the problem of calculating the velocity field within a solitary wave and its celerity and profile, given its height and the depth of water in which it propagates. The first is analytic and approximate and may be regarded as a continuation of the calculations by J. Boussinesq and Lord Rayleigh. The second solution is numerical and is a type of iterative procedure which is necessary to take into account the nonlinear boundary condition which must be imposed on the solution (Bernoulli's theorem). No attempt is made to establish convergence of the iteration procedure, but if convergence is assumed, the method seems to be as accurate as the calculator wishes it to be. The results of the two solutions are compared with experimental results, and it is found that the second method of solution yields results for the velocity components which agree, on the whole, better with the experimental results.

Introduction—The problem is the calculation of the wave profile, the wave velocity (celerity), and the particle velocity components associated with a solitary wave which has a given height in a given depth of water. This problem is a very old one, the first consideration of it being that of *Russell* [1838]. No historical survey will be given, since a recent survey by *Daily* and *Stephan* [1952] is quite adequate. We do not discuss the mathematical question of the existence of a solution to this problem. This question of existence has been recently treated by *Friedrichs* and *Hyers* [1954]. (It was pointed out to me by the editors that a recent paper by *Iwasa* [1955], to which I have not as yet had access, deals also with this general problem.) We shall show in this paper that a partial solution of the problem of *Boussinesq* [1871] and *Rayleigh* [1876] can be extended to the calculation of particle velocities and we shall also present a numerical solution.

Symbols—The following symbols are used.

b	$d[(1+\alpha)/3\alpha]^{\frac{1}{2}}$
c	celerity of the wave
c_0	initial measured celerity
c_s	celerity as defined by Stokes for periodic waves
d	mean depth of the water
d_0	initial measured depth
$F(x)$	function used in the analysis
g	gravitational constant
h	height used in the discussion
H	wave height
H_0	initial measured wave height
l	length used in the discussion
$q(z)$	complex velocity
$Re\ q(z)$	$u(x, y)$
$-Im q(z)$	$v(x, y)$
t	time
$u(x, y)$	$\partial\phi/\partial x$, horizontal velocity component
$v(x, y)$	$\partial\phi/\partial y$, vertical velocity component
$u(s)$, $v(s)$	velocity components on $Y(x)$
u_0, v_0	initial velocity components on $Y_0(x)$
u_n, v_n	velocity components at the nth iteration
x	horizontal coordinate measured from the crest
y	vertical coordinate measured from the bottom
$Y(x)$	profile of the wave
$Y_0(x)$	initial measured profile
$Y_n(x)$	profile at the nth iteration
z	$x + iy$
α	ratio of H to d
ϕ	velocity potential
ψ	stream function

Boussinesq-Rayleigh solution—We choose a coordinate system which moves with velocity c so that the wave crest is stationary. This means that we superimpose a mass movement of the water of velocity $-c$ in the x direction. The y axis is directed vertically upwards, and the line $y = 0$ is the ocean bottom. We let the undisturbed water depth be d.

The problem is to find both an harmonic function $\phi(x, y)$, the velocity potential, satisfying Bernoulli's equation on the free surface and having zero normal derivative on the ocean bottom and an x derivative equal to $-c$ for large x, and the equation for the free surface $Y(x)$ which is

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to be a streamline. More concisely, these conditions are

$$\frac{\partial \phi}{\partial y} = 0 \quad \text{on} \quad y = 0; \tag{1}$$

$$\left(\frac{\partial \phi}{\partial x}\right)^2 + \left(\frac{\partial \phi}{\partial y}\right)^2 + 2g[Y(x) - d] = c^2 \tag{2}$$

on the free surface

$$\lim_{x \to \infty} \frac{\partial \phi}{\partial x} = -c \tag{3}$$

$$\psi = \text{constant} \tag{4}$$

on the free surface, where ψ is the stream function, and

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \tag{5}$$

A solution can be found by putting, following Lamb [1932]

$$\phi = F(x) - \frac{y^2}{2!} F^{\mathrm{I}}(x) + \frac{y^4}{4!} F^{\mathrm{IV}}(x) - \cdots \tag{6}$$

Clearly ϕ is a solution of Laplace's equation, Eq. (5). The conjugate harmonic function ψ, the stream function, is

$$\psi = yF^{\mathrm{I}}(x) - \frac{y^3}{3!} F^{\mathrm{III}}(x) + \frac{y^5}{5!} F^{\mathrm{V}}(x) \cdots \tag{7a}$$

The free surface must be a streamline, on which the value of ψ is just $-dc$, that is

$$\psi = -dc \tag{7b}$$

on the surface.

We assume that the higher order derivatives of $F(x)$ may be safely neglected so that after the partial derivatives of (6) with respect to x and y are substituted into (2), the derivatives of $F(x)$ may be eliminated by successive approximations by use of (7). The boundary condition will be a differential equation of infinite order for $Y(x)$. This condition is replaced by one of finite order by neglecting all derivatives and products of derivatives whose order is greater than the second. By means of these manipulations we find that $Y(x)$ satisfies a nonlinear second-order differential equation

$$\frac{1}{Y^2} + \tfrac{3}{2}\frac{Y^{\mathrm{II}}}{Y} - \tfrac{1}{2}\left(\frac{Y^{\mathrm{I}}}{Y}\right)^2 = \frac{1}{d^2} - \frac{2g(Y-d)}{c^2 d^2} \tag{8}$$

If we multiply by the integrating factor $Y^{\mathrm{I}}(x)$ and integrate, choosing $Y^{\mathrm{I}}(x) = 0$ at $Y(x) = d$ (far away from the wave the ocean surface is flat), we obtain

$$(Y^{\mathrm{I}})^2 = \frac{3(Y-d)^2}{d^2}\left(1 - \frac{gY}{c^2}\right) \tag{9}$$

Since $(Y^{\mathrm{I}})^2$ is always nonnegative, the maximum value of $Y(x)$ is c^2/g, and we find

$$c^2 = g(d + H) \tag{10}$$

where H is the height of the wave (since $Y^{\mathrm{I}} = 0$ also at the crest of the wave). Integrating again, we have

$$Y(x) = d\left(1 + \frac{2\alpha}{1 + \cosh \dfrac{x}{b}}\right) \tag{11}$$

where we have put

$$b = d\left(\frac{1+\alpha}{3\alpha}\right)^{1/2} \tag{12}$$

and

$$\alpha = H/d \tag{13}$$

These results were obtained by *Rayleigh* [1876] and, with minor modification, by *Boussinesq* [1871].

We can now make an approximate calculation of the particle velocity components. From (7) we obtain an expression for $F^{\mathrm{I}}(x)$

$$F^{\mathrm{I}}(x) = -\left[\frac{dc}{Y(x)} + \frac{Y^2(x)}{3!}\left(\frac{dc}{Y(x)}\right)^{\mathrm{II}} + \cdots\right] \tag{14}$$

After computing the indicated derivatives and performing considerable algebra, we find

$$F^{\mathrm{I}}(x) = -C\left[1 - \frac{4\alpha}{\left(2\alpha + 1 + \cosh \dfrac{x}{b}\right)} + \frac{\alpha(\alpha+2)}{(\alpha+1)\left(1 + \cosh \dfrac{x}{b}\right)} - \frac{\alpha^2}{(\alpha+1)\left(1 + \cosh \dfrac{x}{b}\right)^2}\right] \tag{15}$$

where we have neglected derivatives and products of derivatives whose order was greater than second.

From (6) we see that $\partial\phi/\partial x$ along $y = 0$ is just $F^{\mathrm{I}}(x)$. We may consider u, which is $\partial\phi/dx$, to be the real part of a complex velocity $q(z)$, where z is $x + iy$; that is [Lamb, 1932, sec. 62]

$$q(z) = u - iv \tag{16}$$

Since we know $q(z)$ along $y = 0$, we may extend $q(z)$ to the whole complex plane by analytic continuation. We see that

$$q(z) = F^1(z) \tag{17}$$

Separating into real and imaginary parts, we obtain u and v. We transform to a stationary coordinate system by replacing x by $(x - ct)$, and u by $(u - c)$. Then we find that

$$u = c\left[\frac{4\alpha\left(2\alpha + 1 + \cosh\frac{x-ct}{b}\cos\frac{y}{b}\right)}{\left(2\alpha + 1 + \cosh\frac{x-ct}{b}\cos\frac{y}{b}\right)^2 + \sinh^2\frac{x-ct}{b}\sin^2\frac{y}{b}} - \frac{\alpha(\alpha+2)\left(1 + \cosh\frac{x-ct}{b}\cos\frac{y}{b}\right)}{(\alpha+1)\left(\cosh\frac{x-ct}{b} + \cos\frac{y}{b}\right)^2} + \frac{\alpha^2\left(\left\{1 + \cosh\frac{x-ct}{b}\cos\frac{y}{b}\right\}^2 - \sinh^2\frac{x-ct}{b}\sin^2\frac{y}{b}\right)}{(\alpha+1)\left(\cosh\frac{x-ct}{b} + \cos\frac{y}{b}\right)^4}\right] \tag{18a}$$

and

$$v = c\left[\frac{4\alpha\sinh\frac{x-ct}{b}\sin\frac{y}{b}}{\left(2\alpha + 1 + \cosh\frac{x-ct}{b}\cos\frac{y}{b}\right)^2 + \sinh^2\frac{x-ct}{b}\sin^2\frac{y}{b}} - \frac{\alpha(\alpha+2)\sinh\frac{x-ct}{b}\sin\frac{y}{b}}{(\alpha+1)\left(\cosh\frac{x-ct}{b} + \cos\frac{y}{b}\right)^2} + \frac{2\alpha^2\sinh\frac{x-ct}{b}\sin\frac{y}{b}\cdot\left(1 + \cosh\frac{x-ct}{b}\cos\frac{y}{b}\right)}{(\alpha+1)\left(\cosh\frac{x-ct}{b} + \cos\frac{y}{b}\right)^4}\right] \tag{18b}$$

The numerical evaluation of these equations will be discussed in section 5 and compared with experimental values.

Numerical solution—The procedure chosen for constructing a numerical solution was somewhat different in that it seemed to be more convenient to calculate the particle velocity components directly instead of introducing a velocity potential. The goal was the same however—to calculate the profile, the velocity components, and the celerity. We again assume that a velocity potential exists, so that by using the continuity equation we find that the velocity components are harmonic conjugate functions.

We see that on the bottom $v = 0$ (Eq. 1). Bernoulli's theorem, Eq. (2), may be restated in terms of the velocity components as

$$u^2 + v^2 + 2g[Y(x) - d] = c^2 \tag{19}$$

This is our boundary condition at the free surface, together with the condition that the surface must be a streamline

$$Y^1(x) = \frac{v(s)}{u(s)} \tag{20}$$

which is obtained by differentiation from (4). We have put $u(x, Y) = u(s)$ and similarly for v. Finally we need also (3), which is

$$\lim_{x\to\infty} u = -c \tag{21}$$

in terms of the velocity component. The condition that u and v are derivable from a potential is

$$\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} = 0 \tag{22}$$

and the continuity equation is

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{23}$$

From (1) and (23) we easily derive that

$$\frac{\partial u}{\partial x} = 0 \quad \text{on} \quad y = 0 \tag{24}$$

while from (22) we have that

$$\frac{\partial u}{\partial y} = 0 \quad \text{on} \quad x = 0 \tag{25}$$

assuming symmetry about $x = 0$.

We know that the free surface is a streamline. Then the ratio of v to u is given by (20). Using this equation we can eliminate one of the velocity components from (19), say v, and obtain

$$u(s) = \sqrt{\frac{c^2 + 2gd - 2gY(x)}{1 + [Y^1(x)]^2}} \tag{26}$$

This equation gives a boundary condition connecting the free surface with only one velocity component. Now if we knew c and $Y(x)$, we could

easily calculate u by relaxation and v by use of (22) and (23). Since we do not know c and $Y(x)$, we must make use of an iteration procedure to calculate them. We take $Y_0(x)$ and $c^2 + 2gd$ from experimental values [*Daily* and *Stephan*, 1952]. (We use (11) for $Y_0(x)$, since it represents the experimental profile quite well.) If the experiments were completely accurate and our preceding assumptions justified, no iteration would be necessary. Since neither of these suppositions obtains, we proceed in the following manner. We calculate $u_0(x, y)$ and $v_0(x, y)$ as described above. At our free surface the ratio of $v_0(s)$ to $u_0(s)$ will not be equal to $Y_0{}^{\mathrm{I}}(x)$. We call these values $Y_1{}^{\mathrm{I}}(x)$

$$Y_1{}^{\mathrm{I}}(x) = \frac{v_0(s)}{u_0(s)} \tag{27}$$

Then we can construct the function $Y_1(x)$ numerically, choosing the constant of integration so that the distance from the crest to the bottom is unchanged. This new profile does not in general coincide with $Y_0(x)$. Then we take $Y_1(x)$ as the free surface and repeat the process. The calculations are continued until the results do not change appreciably in an iteration. The convergence of this process will be considered in the next section.

Actually this procedure was modified to make the numerical computation somewhat less laborious. The modification leads to a much easier calculation, although it cannot be said to be any more than an approximation. The approximation is to give the solitary wave a large but finite wavelength. A reflection condition was imposed on u at a distance equal to half this wavelength. This approximation means physically that the trough of the solitary wave, which was at infinity, is brought to a large but finite distance from the crest. We gain considerably in the direction of less numerical work, at what seems a slight cost in accuracy. We also assume that the constant $c^2 + 2gd$, which was obtained from experiments, does not change in an iteration. This would not be an approximation if the assumed wavelength were infinite, but it is necessarily so for the finite case.

The celerity was taken to be the average value of u at the trough. A little calculation will show the distinction between this celerity and the value which would be calculated by the use of *Stokes'* [1847] definition. Stokes' definition may be stated as follows: The celerity of a periodic wave is the average value of the horizontal velocity component over one wavelength at a given elevation and in a coordinate system in which the profile is steady. Thus we have

$$c_s = \frac{1}{l}\int_0^l u(x, h)\, dx \tag{28}$$

assuming that h is less than the trough depth. We can show that the celerity is actually independent of the depth at which the averaging takes place by integrating over a different path (this is permissible since the velocity components are assumed to be derivable from a potential). We see that

$$\int_0^l u(x, h)\, dx = \int_h^0 v(0, y)\, dy + \int_0^l u(x, 0)\, dx + \int_0^h v(l, y)\, dy \tag{29}$$

Since v is zero along $x = 0$ and $x = l$, the result is shown, and we have

$$c_s = \frac{1}{l}\int_0^l u(x, 0)\, dx \tag{30}$$

We can see the relation to our definition of the celerity by integration by parts,

$$c_s = \frac{1}{l}[xu(x, 0)]_0^l - \frac{1}{l}\int_0^l x\,\frac{\partial u(x, 0)}{\partial x}\, dx \tag{31}$$

In the case of infinite wavelength, we can show that this value, c_s, is just the celerity from (21), if we have that

$$\lim_{l\to\infty} \frac{1}{l}\int_0^l x\,\frac{\partial u(x, 0)}{\partial x}\, dx = 0 \tag{32}$$

From consideration of the approximate solution for u, Eq. (18a), we see that $\partial u/\partial x$ approaches zero exponentially for large x, so that the result holds in this case. We cannot verify this for the numerical solution without considerable calculation, but at least it is quite plausible. We see from (31) that the celerity in the case of finite wavelength is somewhat smaller than the celerity of the solitary wave.

Discussion of convergence and some numerical details—The convergence of the process has not been demonstrated. It can be made plausible by considerations which show that errors in the pro-

TABLE 1 – *Comparison of values*

Run[a]	Measured			Relaxation-iteration		
	c_0	d_0	H_0	c	d	H
	ft/sec	ft	ft	ft/sec	ft	ft
P-3	3.71	0.345	0.0914	3.64	0.351	0.0854
P-8	3.50	0.259	0.1318	3.44	0.263	0.1278

[a] In *Daily* and *Stephans* [1952].

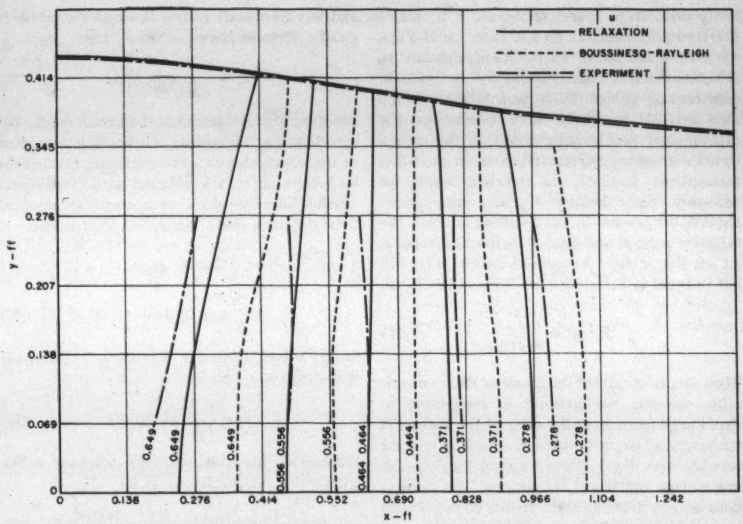

FIG. 1 – Isolines of experimental [*Doily* and *Stephan*, 1952] theoretical [*Boussinesq*, 1871; *Rayleigh*, 1876], and calculated values of u in feet per second, together with a sketch of the experimental and calculated free surface; the wave is that labeled P-3 in *Doily* and *Stephan* [1952]; the celerity is 3.709 ft/sec and the depth is 0.345 ft

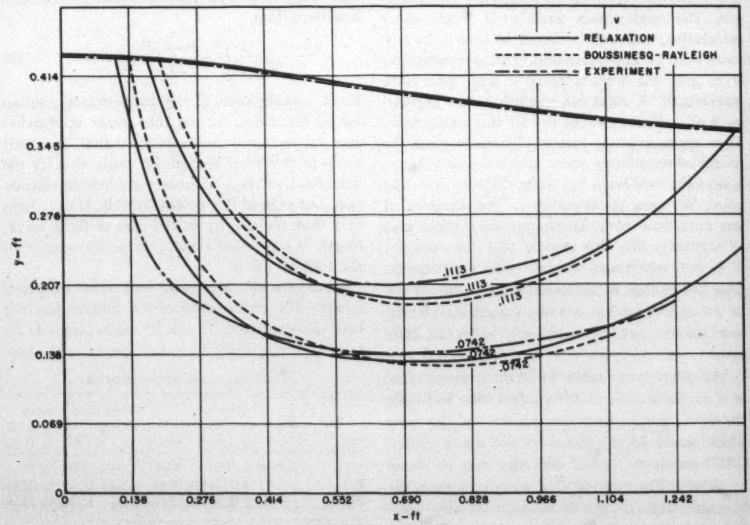

FIG. 2 – Isolines of experimental, theoretical, and calculated values of v in feet per second for the wave considered in Figure 1

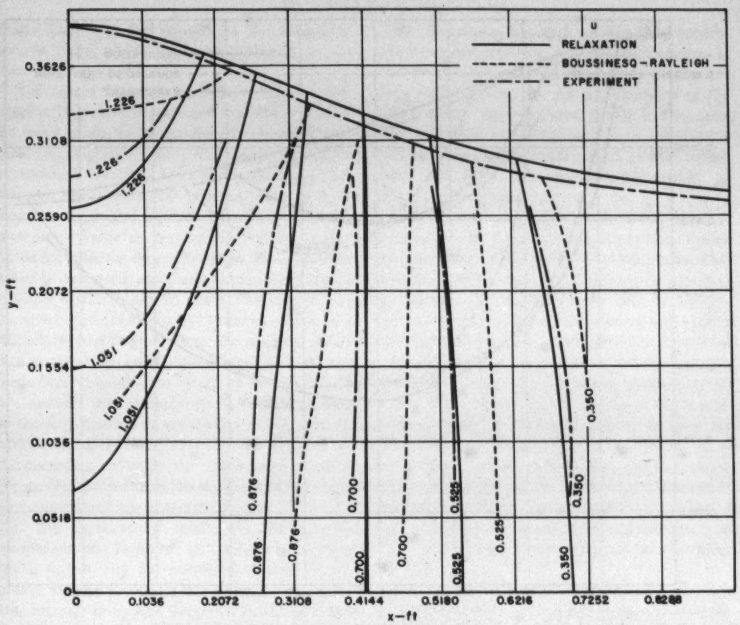

FIG. 3 – Isolines of experimental, theoretical (Boussinesq-Rayleigh), and calculated values of u in feet per second, together with a sketch of the experimental and calculated free surface; the wave is that labeled P-8 in *Daily* and *Stephan* [1952]; the celerity is 3.502 ft/sec and the depth is 0.259 ft

file will tend to correct themselves. The argument does not show that corrections are smaller than the errors, however. Let us assume that there is a correct solution to the problem in the neighborhood of our trial solution. If this is true, then in regions in which the assumed profile is too low this assumed profile will cut streamlines of the actual velocity field, and the direction of the flow at each point on the assumed profile will not coincide with the direction of the profile at this point. In fact we see that the slope of the profile will be less than the slope of the velocity vector (since they are both negative). Then if we let the direction of the velocity field on our assumed profile be the new slope and integrate this slope, choosing the integration constant so that the distance from the crest to the bottom is unchanged, we obtain a profile which will rise toward the correct profile. A similar argument would hold if the assumed profile were too high, so the errors would tend to be self-correcting. We cannot show by this argument that the corrections would not tend to be overcorrections. Thus we cannot rule out an oscillation of the calculated profile a priori. One limitation seems quite necessary. We must at all times be close to the solution we wish to calculate, since there is no assurance of convergence to any particular solution. We try to avoid this difficulty by starting with the experimental values.

The actual mechanics of the relaxation process are treated in a concise fashion by *Jeffreys* [1950] and in much more detail by *Southwell* [1946]. Since the free surface was known accurately at each stage of the iteration, there was no difficulty in calculation of the irregular relaxation patterns associated with the boundary. It was necessary to compute u to four significant figures in order that the differentiation necessary to find v could be correct to three figures. Actually the calculations are not this accurate, since in the relaxation procedure it is not possible to liquidate the residuals in the last significant figure beyond plus or minus two. It was, however, rather easy

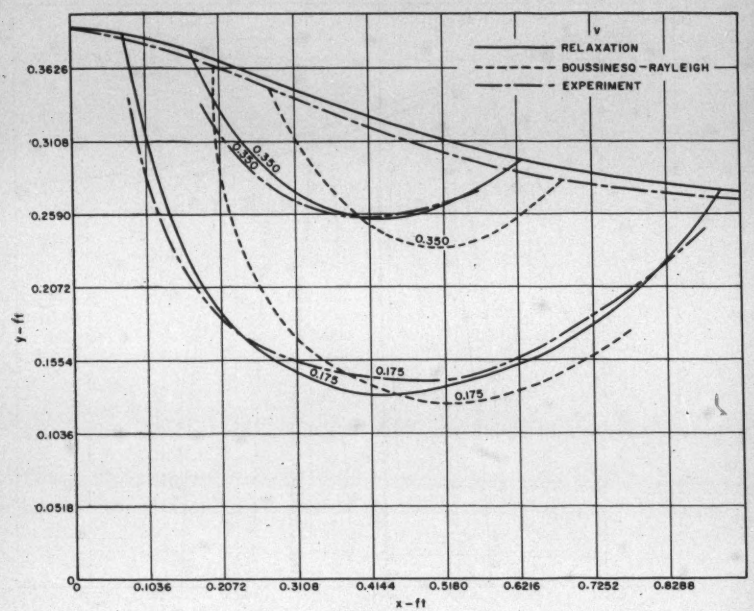

FIG. 4 – Isolines of experimental, theoretical, and calculated values of v in feet per second for the wave considered in Figure 3

to obtain a velocity field and a profile with only a few steps in the iterative procedure that satisfied the boundary conditions within the accuracy of the calculations.

A grid of dimensions two-tenths the measured depth was used in the relaxation calculations. It was found that an advance to a net of half these dimensions changed the calculated values by an amount which was less than the experimental errors, so that further refinement at present appeared useless. For the higher wave it was necessary to use a grid of finer dimensions around the crest, where the relatively sharp curvature of the profile caused the particle velocities to be less smooth functions of position.

Discussion of results and comparison with experiments—We list in Table 1 the measured depth, height, and celerity of two solitary waves, together with the values determined by the relaxation-iteration procedure. Results are shown graphically in Figures 1 to 4. We notice that all the values are somewhat different, although $d_0 + H_0$ is equal to $d + H$, since we had constructed the solution in this fashion. As is shown by *Daily* and *Stephan* [1952] the celerity obtained from the Boussinesq-Rayleigh formula, (10), is almost exactly equal to the measured celerity.

The celerity of a solitary wave is the velocity with which the profile moves. Since the numerical calculations are carried out in a coordinate system in which the profile does not move, we must, in order to compare with experiment, transform the velocity components by transforming our system of reference. It is customary to transform to a system in which the value of u at infinity is zero. Thus the value of u far from the crest in the system which moves with the wave is the value of the celerity, c.

In our numerical solution 'infinity' was moved to a point whose distance from the crest was six times the measured depth. It seemed that a proper choice of the celerity would be the average value of u on this vertical line at, as it were, 'infinity.' Using *Stokes'* [1847] definition of the celerity would

clearly give only the velocity of the associated periodic wave, which would be too small, as we have seen.

This is not the only possible choice of the celerity. It is possible to argue that the fact that the wave profile is flat at the trough would not upset the calculation, and that the profile should be extended to infinity from there, neglecting this flatness. The asymptotic value of the depth is then d_0, the initial measured depth, and so the asymptotic value of the velocity would be c_0. As we see from the table, the values of the celerity would be increased, and the isolines of u in Figures 1 and 3 would be moved toward the line $x = 0$ (compare just before Eq. (17) and note that in a stationary coordinate system the highest values of u occur at the crest) by an amount which exceeds experimental error by 10 to 15 pct. We do not consider that the agreement with experiment of the first method of calculation of the celerity verifies it, since there exists the possibility of compensating errors in the profile and celerity. (From (26) we see that too small a celerity could be compensated by a greater depth.)

If the experimental results for the velocity components are inspected in a coordinate system which moves with the measured velocity of the profile, and the values are extrapolated in a reasonable manner in toward the crest, it will be found that the experimental values of the velocity components and those calculated by relaxation-iteration will agree quite well in this region, but that deviations will occur as one looks at values away from the crest. The calculated values will be significantly smaller than the experimental values, just because of the reflection condition which was imposed on the calculations at the trough. The choice of method of calculating the celerity was made partly with the view of preserving this agreement.

In Figures 1 to 4 the calculated and experimental profiles have been plotted, together with isolines of horizontal and vertical velocity components. We see by examination of the isolines that the calculated (relaxation-iteration) values of the horizontal velocity component are about the same as the experimental values, with the approximate values (Boussinesq-Rayleigh) somewhat larger.

The agreement with the experimental values of the velocity components is good, being within the limits of the experimental error for the relaxation-iteration solution and not too far removed for the Boussinesq-Rayleigh solution. The vertical velocity components are in satisfactory agreement with the experimental values, and the profiles are quite similar, except in the neighborhood of the trough where the calculated profile has to raise itself in order to flatten out in a continuous fashion. The Boussinesq-Rayleigh profile agrees quite well with the experimental profile, as explained previously.

The fact that the profile at the trough is calculated to be higher than the observed profile causes the calculated celerity to be somewhat smaller than the observed celerity. This could be remedied by enlarging the distance from crest to trough, but it seems unnecessary in view of the experimental errors and the length of the calculations.

Conclusions—The numerical solution is an improvement over the Boussinesq-Rayleigh solution of the problem, since the fit to all the experimental values is reasonably good. In fact for calculation of the velocity components, it is unnecessary for all practical purposes to perform any iterative procedure. Only one relaxation is necessary to obtain quite satisfactory values of the velocity components. The readjustment in the values was of a minor nature in all the calculations.

The results depend most strongly upon the imposition of the reflection condition at the trough. The errors caused by this condition may be progressively reduced by taking longer and longer wavelengths. However, it is possible to avoid this difficulty by use of conformal mapping (taking care to correct the boundary conditions), where a similar iterative procedure would be applied after mapping of the wave into a finite region. This was not attempted since it seemed that an adequate solution for practical purposes had already been obtained.

The numerical technique used would be even better adapted to calculation with waves which have a finite wavelength. In that case, and assuming convergence, it is clearly possible to calculate all properties of the wave in a systematic manner from a good initial guess of the profile. Such a calculation has many engineering uses for those who design structures which must withstand ocean waves.

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Permeameter Wall Effect

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Abstract—If the resistance to flow through a granular medium is to be measured in the laboratory with a permeameter, care must be exercised in interpreting the results so as to account for wall effect. A cursory analysis presented in this paper indicates that in general the ratio of permeameter diameter to mean particle diameter should exceed about 40 to eliminate any sizeable effect of the container wall. For ratios less than 40 the Reynolds number of the flow has great influence on wall effect.

Notation—The following symbols and terminology are used.

α	porosity, void volume divided by total volume
D	diameter of a cylindrical tube permeameter
d	diameter of spherical particle
$F(\alpha)$	porosity factor for turbulent flow $[(1 - \alpha)/\alpha^3]$
ψ_w	resistance to flow with container wall
ψ	resistance to flow (no container wall)
R	Reynolds number, dV/ν where ν is kinematic viscosity
S	surface area
V	velocity of flow, rate of flow divided by gross cross-sectional area

Introduction—Container walls have two effects on the resistance to flow offered by a confined granular medium. It was observed by *Graton* and *Fraser* [1935] that porosity is greater in the immediate vicinity of the container walls than in the body of the medium. This is reasonable as a particle in contact with the container wall has only two degrees of freedom while one in the body of the medium has three. Particles with two degrees of freedom will not pack together as tightly as those with three and hence will have a higher porosity. This increased porosity will effectively reduce the resistance to flow of the confined medium. The other effect of the wall is an increased resistance to flow due to the surface area of the wall. These two effects oppose one another and their relative importance depends on the character of the flow.

Characteristics of flow—The flow of fluids is classified as laminar, turbulent, or transitional. Various investigators [*Blake*, 1922, *Bakhmeteff*, 1937, and others] observed by experiment that if Reynolds number is less than about five the flow through a granular medium will be laminar. In laminar-flow shear stress in the fluid is responsible for fluid friction and it is reasonable to assume that the presence of a container wall will increase the resistance to flow because of the additional surface area on which the shear stresses may act.

At Reynolds numbers slightly above five turbulence starts to develop in the larger pore spaces and the head loss through the medium will no longer be directly proportional to V as for the case of laminar flow. *Rose* and *Risk* [1949] and *Ergun* and *Orning* [1949] have shown experimentally that fully developed turbulent flow through a granular medium (head loss proportional to V^2) does not occur until R reaches about 5000. Because fluid resistance in turbulent flow depends mostly on inertial effects it is logical to assume that the increased porosity near the container wall will play an important part in influencing the flow when $R > 5000$ while the additional surface area will have little effect.

Analysis of wall effect—Assume that a medium made up of equal sized spheres (diameter d) is contained in a cylindrical tube of diameter D. Consider the medium to be made up of two volumes, a core of diameter $(D - d)$ and an outer shell. The cross-sectional area of the core is $(\pi/4)(D - d)^2$ and of the shell, $(\pi/4)[D^2 - (D - d)^2] = (\pi/4)(2Dd - d^2)$.

As previously mentioned, the spheres near the wall are not packed as tightly as those in the interior. Hence, the porosity of the spheres in the shell must be greater than in the core. To get a start on this problem, the volume occupied by a certain quantity of #9 lead shot was measured in glass cylinders of various diameters. The lead shot were poured into the cylinders in the dry loose state and subjected to a minimum of vibration. The average results of several trials using 2028 grams of the shot (specific gravity = 10.91) are shown in Table 1. A plot of these data (Fig. 1) indicates that as $D/d \to \infty$, the apparent porosity becomes about 37.8 pct. Hence, it will be assumed that for this particular mode of packing the porosity of the spheres in the core is 37.8 pct. Using information from Figure 1 and assuming the

core porosity α_C to be 37.8 pct, the shell porosity α_S can be computed for various D/d ratios since

$$D^3\alpha_M = (D - d)^3\alpha_C + (2Dd - d^3)\alpha_S$$

or

$$(D/d)^3\alpha_M = (D/d - 1)^3\alpha_C + (2D/d - 1)\alpha_S \quad (1)$$

The term α_M represents the apparent or mean porosity of the medium. Table 2 shows the computed results. Thus it is seen that the average porosity of the spheres in the assumed shell of thickness $d/2$ depends on the D/d ratio.

Laminar flow—If it is assumed that the container wall has as much frictional resistance per unit area as the spheres comprising the medium, then

$$\frac{\psi_W}{\psi} = \frac{(S)_C + (S)_S + (S)_W}{(S)_C + (S)_S} \quad (2)$$

where the S's refer to surface area of spheres in the core and shell and to surface area of the container wall. In the core

$$\frac{\pi d^3}{6} \times n_C = \frac{\pi}{4}(D - d)^2(1 - \alpha_C)$$

Hence

$$n_C = \frac{3}{2}\frac{(D - d)^2}{d^3}(1 - \alpha_C)$$

where n_C represents the number of spheres in the core per unit of length. Thus

$$(S)_C = n_C \times \pi d^2 = \frac{3\pi}{2d}(D - d)^2(1 - \alpha_C)$$

Similarly

$$(S)_S = n_S \times \pi d^2 = \frac{3\pi}{2d}(2Dd - d^2)(1 - \alpha_S)$$

and $(S)_W = \pi D$ and thus

$$\frac{\psi_W}{\psi} = \frac{\frac{3\pi}{2d}(D - d)^3(1 - \alpha_C) + \frac{3\pi}{2d}(2Dd - d^3)(1 - \alpha_S) + \pi D}{\frac{3\pi}{2d}(D - d)^3(1 - \alpha_C) + \frac{3\pi}{2d}(2Dd - d^3)(1 - \alpha_S)}$$

$$= \frac{(D/d - 1)^3(1 - \alpha_C) + (2D/d - 1)(1 - \alpha_S) + \frac{2D}{3d}}{(D/d - 1)^3(1 - \alpha_C) + (2D/d - 1)(1 - \alpha_S)} \quad (3)$$

TABLE 1 – *Results of packing tests*

Diam. of cylinder	Measured volume	D/d ratio	Apparent porosity $(\alpha)_M$
inch	milliliters		pct
0.39	338.0	4.8	45.6
0.59	320.5	7.2	42.0
1.00	311.0	12.2	40.2
1.38	305.0	16.8	39.1
2.35	302.5	28.7	38.5
2.89	301.0	35.3	38.3

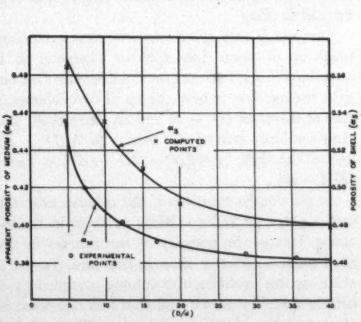

FIG. 1 – Plot of porosity vs. D/d

TABLE 2 – *Computed results based on packing tests*

D/d	α_C	α_M[a]	α_S
5	0.378	0.445	0.564
10	0.378	0.408	0.536
15	0.378	0.395	0.510
20	0.378	0.389	0.491
40	0.378	0.383	0.479

[a] Value taken from Figure 1

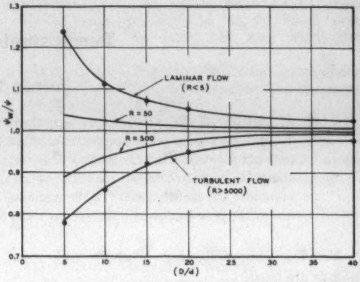

FIG. 2 – Plot of ψ_W/ψ vs. D/d

TABLE 3 – *Basis for curves of figure 2*

R	Increased surface area effect	Increased porosity effect
5	1.00	0
50	0.67	0.33
500	0.33	0.67
5000	0	1.00

Substituting the respective values of α_C, α_M and those of α_S as computed from (1), results in:

D/d	ψ_w/ψ
5	1.24
10	1.12
15	1.07
20	1.055
40	1.03

These factors are presumed to be applicable if $\mathbf{R} < 5$. They represent the increased resistance to flow caused by the surface area of the permeameter wall.

Turbulent flow—Fair and *Hatch* [1933] have proposed that for the case of turbulent flow through granular media the porosity of the medium influences the fluid resistance according to the ratio $(1 - \alpha)/\alpha^3$. This was later substantiated experimentally by *Hatch* [1943]. Assuming for turbulent flow that the increased porosity near the container wall influences the flow many times more than the increased surface area

$$\frac{\psi_w}{\psi} = \frac{(D/d)^2[F(\alpha)]_M}{(D/d-1)^2[F(\alpha)]_C + \left(\frac{2D}{d} - 1\right)[F(\alpha)]_S} \quad (4)$$

where $[F(\alpha)]$ represents the porosity factor $[(1 - \alpha)/\alpha^3]$ for the core C, shell S, and medium of mean porosity α_M.

Putting into (4) the previously mentioned values of α_C, α_M, and α_S yields:

D/d	ψ_w/ψ
5	0.78
10	0.86
15	0.92
20	0.955
40	0.98

These factors are presumed to be applicable if $\mathbf{R} > 5000$. They represent the reduced resistance to flow created by the increased porosity in the vicinity of the container wall.

Transitional flow—If the Reynolds number of the flow through a granular medium lies between 5 and 5000 the head loss is proportional to V^n where n is between one and two. At values of R slightly greater than five the viscous effects predominate but inertial effects begin to become important. The wall effect for transitional flow $(5 > \mathbf{R} > 5000)$ can be approximated by pro-rating the 'increased surface area' effect and the 'increased porosity' effect. The curves of Figure 2 were plotted by pro-rating the two effects on the basis shown in Table 3. Note that there is no logical basis for assuming a logarithmic variation of the effects. It was simply chosen for convenience.

Discussion—The curves of Figure 2 indicate that wall effect depends on $\mathbf{R}$ as well as the D/d ratio. These curves follow the same pattern as those of *Rose* and *Rizk* [1949] who conducted extensive experiments on permeameter wall effect. Their results indicate that wall effect is somewhat more pronounced than as shown in Figure 2. If in using a permeameter one has to correct for wall effect, he should use the results of *Rose* and *Rizk* [1949]. The curves of Figure 2 merely give an indication of the trend of wall effect and do not represent true values.

The analysis presented here is based on a granular medium consisting of spheres of uniform size. The D/d ratio for irregularly shaped particles of varying size can be determined by computing the average effective particle diameter by the method proposed by *Fair* and *Hatch* [1933]. Wall effect for irregularly shaped particles will be about the same as for uniform spheres and the D/d ratio should exceed 40 to eliminate the necessity of making a correction for wall effect.

Conclusion—Permeameter wall effect depends on the Reynolds number of the flow as well as the D/d ratio. If $D/d > 40$ wall effect is of negligible magnitude. These conclusions are based on the analysis presented here and have been verified experimentally by *Rose* and *Rizk* [1949].

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A Floating Lysimeter and Its Evaporation Recorder

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Abstract—A weighing lysimeter is described which operates on Archimedes principle and which has been used to obtain continuous values of evapotranspiration from an irrigated pasture. Some errors in evaluation of evapotranspiration by means of a lysimeter are discussed.

Introduction—Evaluation of evapotranspiration by means of a lysimeter requires that the lysimeter be indistinguishable from the surrounding area. Evapotranspiration measured with a lysimeter will not be representative of that from the surroundings if the crop in the lysimeter is either taller, shorter, denser, or thinner, if there is a non-cropped area at the lysimeter periphery, or if the moisture availability in the lysimeter is different from that under the surrounding crop.

A photograph (Fig. 1) of the lysimeter described here indicates the appearance of a properly exposed (indistinguishable) lysimeter. The response of the crop in such a lysimeter to the microclimatic environment will be very much like that of a crop growing naturally at the same site. It is emphasized that a properly exposed lysimeter placed in a small plot will measure the evapotranspiration from that site in that plot, but if the lysimeter is to evaluate evapotranspiration from a large area then it must be in the center of a large, uniform area.

Even with an indistinguishable lysimeter the measured evapotranspiration should be corrected for an often overlooked error. That is, the effective area of a lysimeter is likely to be different from the actual area within the lysimeter walls. Thus, the volume of water evaporated per unit area of the lysimeter tank will likely be different from the depth lost over the surrounding area. *Pasquill* [1950] was able to detect a difference in effective area for two small evaporimeters.

We propose that the effective area of a properly exposed lysimeter can be found from vertical heat-budget measurements during periods when horizontal heat divergence terms are negligible (low wind and no large horizontal temperature gradients). Thus heat-budget measurements can be used to calibrate the lysimeter continually. When suitable precautions are taken to maintain lysimeter representativeness, to prevent heat-divergence errors specific to the lysimeter by proper lysimeter exposure, and to maintain a calibration of effective area; a lysimeter can be used to provide detailed evapotranspiration data. A lysimeter is described which provides such data.

General description—The lysimeter design, which makes use of Archimedes principle, is a modification of one used by *Suomi* [1953] in evaluation of evapotranspiration from corn grown on a peat soil. Modifications made were to increase the tank depth from two to six feet, to increase the buoyancy to permit use with mineral soils, and to improve the sensitivity and remoteness of the recorder. The lysimeter shown (Fig. 2) has been installed in a sprinkler-irrigated alfalfa-brome pasture on Plainfield sand near Hancock, Wisconsin.

Soil is placed in a hollow-walled tank that floats in water inside a slightly larger reservoir tank. A loss or gain of weight in the floating tank results in a change of water level in the reservoir tank and stilling well. This level is recorded by a sensitive water-level recorder. The design is such that the weight changes are recorded as equivalent depth of water loss over the tank area accurate to ±0.025 mm. Any overflow from an excessive weight on the floating tank is retained in an overflow tank at the recorder.

Design relationships—A loss of water of mass ΔM from the floating tank has the equivalent depth of water loss

$$\Delta d_w = \Delta M / A_s D_w$$

where A_s is the surface area of the floating tank and D_w is the density of water. This mass change will result in a change of water level in the reservoir tank and stilling well

$$\Delta h_w = \Delta d_w A_s / (A_s + A_w)$$

where A_w is the area of the annular water surface plus the area of the stilling well, and h_w is measured relative to a fixed datum. For this design A_s = 19.6 ft², A_w = 3.5 ft², and so $\Delta h_w = 0.85 \Delta d_w$. The change in height of the floating tank Δh_t with respect to a fixed datum is small

$$\Delta h_t = \Delta d_w A_w / (A + A_w)$$

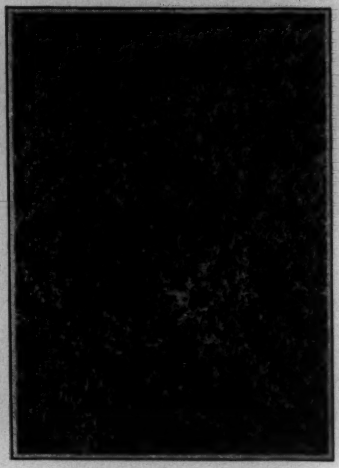

FIG. 1 – Photograph of crop cover showing that the lysimeter (inside the curve) was indistinguishable from the surroundings

which for this lysimeter is $h_t = 0.15\ d_w$. The water level recorders were made with mechanical amplification of 1/0.85 and 10/0.85 to record Δd_w and $10\Delta d_w$ directly on a chart. It is desirable to have A_w as small as possible for good sensitivity. One practical limit is the needed clearance between the floating and reservoir tanks. Another is that it is desirable to have large diameter floats to supply sufficient force to actuate the recorder mechanism.

Top soil is placed over the air chamber in the floating tank to achieve a narrow non-cropped border area. With this arrangement there is less soil volume for rooting, and in addition the floating tank is top heavy. The decrease in rooting volume is not serious if the crop is well irrigated and fertilized, and when percolate is not allowed to accumulate above the tank bottom.

Ballast (steel punchings) at the bottom of the air chamber maintain stable flotation throughout an allowed moisture (weight) change Δd_w of two inches. The center of gravity has a maximum height of 31.5 inches above the tank bottom and the center of buoyancy has a minimum height of

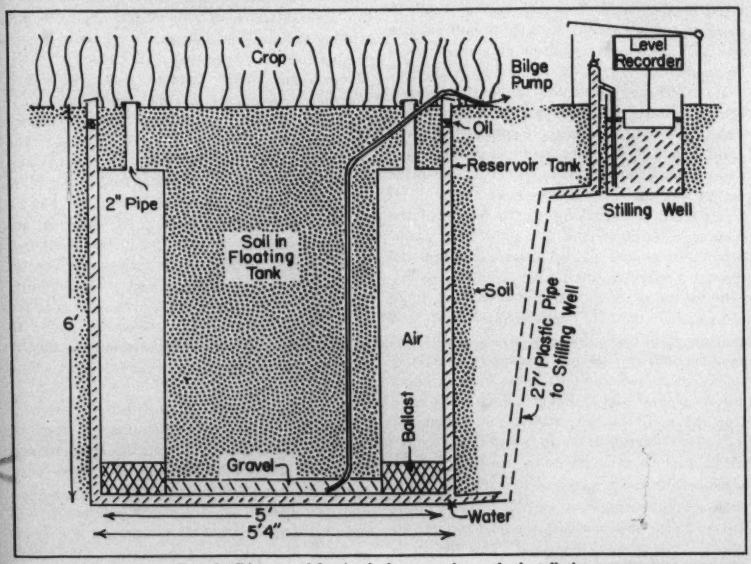

FIG. 2 – Diagram of floating lysimeter and recorder installation

33.5 inches above the bottom for this lysimeter in operation.

The present tank buoyancy should be retained for a fine-textured soil of lesser bulk density than that for which it was designed (1.7 gm/cm³). This is because of the greater maximum wet weight, and greater evaporation between irrigations that would be allowed if such a soil were used.

The reservoir tank was constructed from a 1000 gal, 10 gage fuel tank. The floating tank was formed from a 200 gal, 14 gage fuel tank, and a shrunk 1000 gal tank. They were constructed by Peterson Tank Co., Madison, Wis. at an approximate cost of $535. Detailed shop plans for the lysimeter and recorders as constructed are available from the authors.

Design modifications—After the lysimeter was in operation it was realized that vertical columns or blocks of Styrofoam could have been buried in the soil of the floating tank on a regular grid pattern to eliminate the need for the air chamber. (Styrofoam is expanded polystyrene manufactured by Dow Chemical Co. It is waterproof and has a density of 1.5 lbs/ft³.) These blocks would still decrease the soil volume for rooting, but the present shallow depth of soil over the air chamber could be eliminated. This construction would be more economical since only a false bottom with two inch-pipe risers for ballast adjustment would be required.

It would be practicable to weigh a heavy lysimeter tank with conventional low capacity scales if the tank were partially immersed in water or other fluid. A necessary condition would be that there is a constant depth of immersion when the weight is obtained. In the design of *Arthur* [1955] water could be added up to the height of the opening in the outer tank. For other scales waterproof seals around the lysimeter tank supports, through a reservoir tank bottom, could be made.

Water-level recorders—On a common chart drum, one recorder (the 1:1) traces the actual Δd_w and another (the 10:1) traces $10\Delta d_w$. Mechanical amplification is obtained through the relative lengths of the pen and float arms. Each weighted float is counter-balanced over a fulcrum to bring the float about half-way out of water. Figure 3 shows the operation of the 10:1 recorder.

The 10:1 recorder pivots on razor-blade knife edges resting in a V-notch of tool steel. A razor-blade stirrup, resting in an annular V on the stainless steel float arm, suspends the float through an adjustable length of brass rod. This length is adjusted to keep the 10:1 pen on scale. A Δh_w of 0.025 mm will change the buoyancy of the ten-

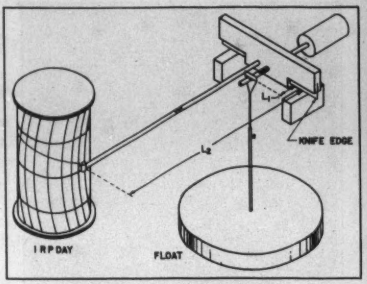

FIG. 3 – The 10:1 recorder; the lengths of the pen arm (L_2) and float arm (L_1) are such that $L_2/L_1 = 10(A_s + A_w)/A_s$.

inch diameter float by 1.3 gm. This force will overcome the low friction of the pivots plus that of a lightly bearing pen on the chart. The less sensitive 1:1 recorder is pivoted in plain cone-shaped bearings and has a smaller float. This float is suspended by a fine wire of non-adjustable length.

Fluctuations in the water level due to gusts of wind on the floating tank are damped by choosing an appropriate sized siphon tube between the stilling well and the side arm of an air trap connected to the underground plastic pipe.

Field installation—Concrete bases were poured for the reservoir tank and the recorder assembly. Soil horizons were back filled in natural sequence into the floating tank as water was added to the reservoir tank. After the soil was irrigated and had settled, the floating tank was leveled by adding ballast through the appropriate filler pipes (Fig. 2). Transformer oil was poured on the water surface in the reservoir tank and stilling well to about one-half inch depth. Three curtain springs which center the floating tank were placed horizontal and under light tension. Recorder float arms were adjusted in length to give a correct trace on the chart with known weights placed on the floating tank. Finally the lysimeter and surroundings were smoothed and seeded.

It is very important not to disturb the area near a lysimeter while obtaining readings. Except for clipping the pasture, traffic near this lysimeter was limited to the recorder stationed 25 ft to the east, the usual downwind direction.

Results and discussions—Three separate days of recorded data during 1955 are presented (Fig. 4) as being illustrative of the type of daily record obtained from the lysimeter.

In Figure 5 is plotted the ratio of evapotrans-

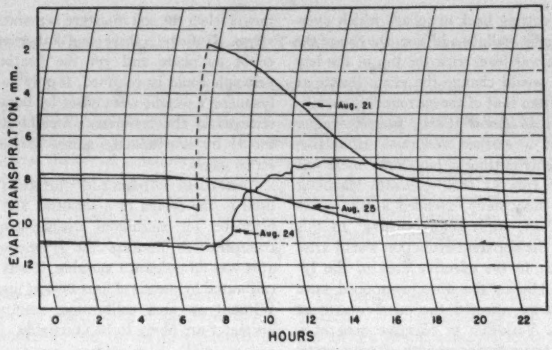

FIG. 4 – Daily records of evapotranspiration: Aug. 21, clear, hot, and windy; Aug. 24, rainy; Aug. 25, overcast

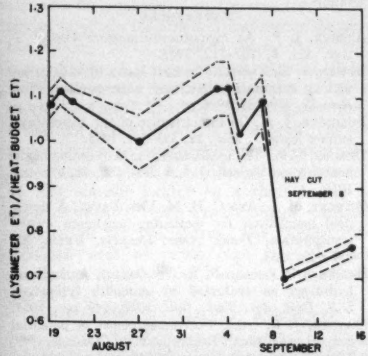

FIG. 5 – The ratio of lysimeter evapotranspiration (ET) to heat budget evapotranspiration before and after marked change in lysimeter's effective area; broken lines enclose the maximum possible range in ratio due to errors

piration as determined by the lysimeter to the evapotranspiration found from heat-budget measurements on nine days. The evapotranspiration from the lysimeter was expressed on the basis of the actual soil surface area in the lysimeter. Each solid circle shown indicates a ratio that was constant for a minimum period of two hours. This ratio was constant when there was negligible horizontal divergence of sensible heat (usually from early morning to about 11h 00m, or on overcast days with low wind). Except on overcast days, there was generally increasing divergence after 11h 00m and the ratio of the lysimeter measurement to heat budget measurement increased. The ratios shown in Figure 5 were used to determine the effective area of the lysimeter by assuming that the heat budget method is valid during periods when horizontal heat divergence is negligible.

The equation for the vertical heat budget at the Earth's surface is

$$R_n = S + L + E$$

where R_n is the net radiation arriving at the surface, S is the heat flux into the soil, L is the flux of sensible heat into the air, E is the energy used to evaporate water.

The net radiation and soil heat flux were measured directly [*Suomi* and others, 1954; *Deacon*, 1950]. The remaining two terms were found indirectly by determining the *Bowen* [1926] ratio L/E which is assumed to be proportional to the ratio of the temperature gradient to the vapor pressure gradient near the surface [*Rider* and *Robinson*, 1951; *Businger*, 1955]. That is, when measurements are made *near* the surface

$$L/E = \gamma \Delta T/\Delta e$$

where γ is the psychrometer constant and ΔT and Δe are the temperature and vapor-pressure differences over a small height interval above the crop surface. The temperature and vapor-pressure differences were measured between heights of 40 and 100 cm above the soil (the crop grew as high as 30 cm) by instruments swept over a 50-ft horizontal traverse [*Tanner* and *Suomi*, 1956].

It is noted in Figure 5 that there was a marked change in the lysimeter's effective area after the hay was cut to a short stubble on September 8. The same magnitude change was observed on a July 28 cutting. Part of the reduction probably

was from the cutting back of foliage which overhung the lysimeter wall. In addition, the rim of the lysimeter tank was level with the top of the hay stubble which would change the microclimate at the lysimeter from that of the surrounding area.

Harrold and *Dreibelbis* [1951], from lysimeter records, found a marked reduction in evapotranspiration after cutting of hay. Since there was an uncropped area at their concrete lysimeter walls the hay may have extended a few inches outwards over the walls before cutting. In this event, part of the apparent reduction would arise from a decrease in the effective area of the lysimeters. In addition, the wide, uncropped tank walls undoubtedly affected the microclimate at the lysimeters. Variation in effective area of a lysimeter will occur during growth of most crops and will be of most significance for lysimeters of small actual area or for those with a large periphery to area ratio.

There is no adequate way to estimate the effective area of the lysimeter from tank area overlap corrections or plant counts. For example, *Suomi* [1953] used a lysimeter five-foot in diameter with a tank area of 19.6 ft². Corn was transplanted by hand in rows with uniform row spacings and plant densities comparable to the surrounding area. The effective lysimeter area as determined by plant spacing was 23.8 ft². The lysimeter area determined by heat budget calibration was 16.6 ft².

The lysimeter shown here has been adequate for obtaining a continuous record of evaporation from an irrigated pasture at a low cost. Other continuous-weighing lysimeters of comparable accuracy have required much more expensive installations [*Harrold* and *Dreibelbis*, 1951]. The narrow non-cropped periphery and the moderately large (20 ft²) surface area decrease the error when the effective area is unknown.

The tank was six feet deep and all percolate was pumped from the lysimeter to avoid errors with respect to the evapotranspiration of the surroundings. These errors would be expected [*Mather*, 1954; *Gilbert* and *Van Bavel*, 1954] if a water table is maintained in a shallow tank or if the soil is excessively wet from frequent irrigation to a shallow lysimeter and not to a large, well-drained surrounding area.

The lysimeter as described has some limitations. For example, it is not suitable for measurements of evapotranspiration from an undisturbed soil profile and there is no provision for recording runoff. Because the buoyancy requirement demands a decreased root volume per unit area of surface, the lysimeter is most suited to measurements when the soil moisture is maintained at low stress. However, these and other modifications could be made and yet the floating lysimeter principle could be retained. If only part of a large lysimeter's weight were offset by buoyancy, small changes in the lysimeter's weight could be detected by low-capacity scales [*Arthur*, 1955] or strain gages.

Conclusions—Archimedes principle has been used in the design of a sensitive and economical lysimeter for continuous measurement of evapotranspiration. Because the lysimeter's effective area was an unknown variable, it was continually calibrated by means of heat budget measurements. Without an area calibration, results from any lysimeter are likely to be unreliable.

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The Annual Variations of Sub-soil Temperatures about a 600-foot Circle

Irving A. Singer and Robert M. Brown

Abstract—To assist engineers in the computations of thermal stresses, thermal loads, and the economic depth to which a protron synchrotron should be buried, the Meteorology Group predicted the annual variations of sub-soil temperatures to the depth of 20 ft. Measurements were made at four stations having various types of ground cover, and located on a circle having a diameter of 600 ft. The analysis of one year of data showed that differences of ground cover have an appreciable effect on the temperature at all measuring depths. Standard thermal diffusion coefficients for a sandy soil are too small to account for the observed range of annual temperatures.

Introduction—The proposed construction of a 25 B E V protron synchrotron at the Brookhaven National Laboratory led to the investigation of sub-soil temperatures. This doughnut-shaped structure, having a diameter of 850 ft, must be aligned with great precision. The structure will be buried to obtain the accuracy and reduce the air-conditioning load. To assist engineers in the computations of thermal stresses, thermal loads, and the economic depth to which the structure should be buried, the Meteorology Group predicted the annual variations of sub-soil temperatures. This paper compares the prediction to sub-soil-temperatures at 2.5, 5, 10 and 20 feet measured at four stations located on a circle having a diameter of 600 ft which was the original planned diameter of the synchrotron. The thermal diffusivities were computed from classical heat conduction equations and compared to standard values.

Site—Brookhaven National Laboratory is located approximately at the center of Long Island. The terrain near the Laboratory would be described as relatively flat. Along the north shore and to the east and west of the Laboratory are hills and ridges representing terminal moraines of the glacial periods. None of these exceed an elevation of 200 ft except for isolated peaks (Fig. 1). In the immediate vicinity of the observation area, the maximum height variation over a horizontal distance of 400 ft is 20 ft. Figure 2 shows specific contours of the area and position of the four temperature measuring stations. The main vegetation consists of scrub oak and pine 25 to 30 ft high with open fields of grass. Figure 3, an aerial photograph of the area indicates the type of coverage. The north station is nearly open; the east station has small pine trees widely scattered around it; the south station is within very dense tall pines; and the west station has a heavy growth of tall pines in all directions except east where there is a slight exposure.

The composition and character of the soil are described in a report from the Raymond Pile Co. to the Brookhaven National Laboratory on borings made at the site of the new accelerator. The materials found in each of the fourteen holes are similar, Table 1. The blows needed for a one-foot penetration of the sampling tube in each of the holes also indicated that the density and composition of the soil were homogeneous.

Instrumentation—The Meteorology Group has been making continuous sub-soil temperature measurements for several years at two and six inches, one and 2.5 ft, using *Leeds* and *Northrup* [1942] instrumentation. These measurements were made near their installation which is located one mile west of the proposed synchrotron. For expediency and known reliability, similar instrumentation was used for this study.

The temperatures were measured by means of 100-ohm copper wire resistance thermometers (Thermohms). Their changes in resistance are directly proportional to temperature over the range of interest. All Thermohms were calibrated prior to their installation by comparison with a thermometer calibrated by the National Bureau of Standards. Numerous checks are made each year on the Thermohms in constant use by the Meteorology Group. The error has never exceeded 0.5°C. This was further verified when twelve Thermohms were removed after being in the ground for 18 months. The maximum error was 0.2°C. For protection against corrosion, lead-covered leads of various lengths connect the elements to the recorders.

The Model S recorders are of the Wheatstone bridge type providing single line tracing. The measuring circuit consists of a single, slide-wire bridge and a three-wire (Simens) arrangement for measuring resistance independent of the temperature or length of the lead wires. The four recorders were also calibrated before use in the field and serviced every two months. A −10°C check

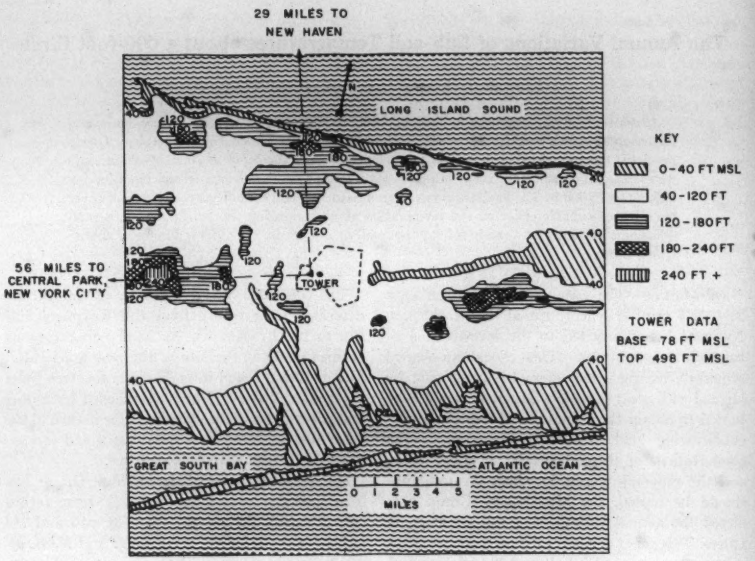

FIG. 1 – Contour map of Brookhaven area

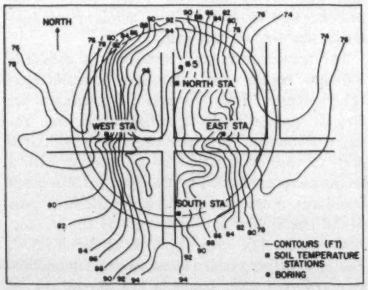

FIG. 2 – Contour map of synchrotron area

coil was installed periodically to verify the scale and accuracy of the recorders. A further recorder test was made by interchanging recorders to verify that the indicated temperature differences at the four stations were real. This showed that the recorded temperatures agreed with each other to 0.01°C. To increase the number of temperature records on one recorder a switching device was constructed. It provided a single line trace switching from level to level and providing a check of the −10°C coil every third minute.

The Thermohms were installed in the following manner. A one-foot diameter hole was made with a post hole digger down to 20 ft. Stove pipe was used to prevent the sand from caving in at lower depths. The Thermohms were put in vertically to the appropriate depths. The stove pipe was removed and the soil replaced. Data were not used for three months to allow settling of the soil.

Data and analysis—A prediction of the extremes in temperature engineers could expect in this soil was made in June 1954. It was based on the classical heat conduction equation

$$\partial\theta/\partial t = \mu/\rho c(\partial^2\theta/\partial z^2) \qquad (1)$$

assuming a semi-infinite medium whose surface temperature is a known periodic function of time, the solution is

$$\theta = (\bar{\theta} - \alpha z) + A_m \exp(-z\sqrt{\pi\rho c/P\mu}) \cdot \cos[2\pi(t - t_m - z\sqrt{\rho Pc/4\pi\mu})/P] \qquad (2)$$

FIG. 3 – Aerial photograph of synchrotron area

TABLE 1 – *Boring Number 5—Elevation 94.3 MSL*

Depth	Type of Soil
ft	
0–2	Topsoil, brown, sandy loam
2–6	Medium brown sand, gravel
6–14	Coarse, brown sand, gravel
14–60	Medium to fine, brown sand, gravel
Water level at 49 ft.	

where

θ = temperature, °C
μ = thermal conductivity, cal/deg cm sec
ρ = specific gravity, gm/cm³
c = specific heat, cal/gm deg
$a = \mu/c\rho$ = thermal diffusivity, cm²/sec
z = depth, cm
α = lapse rate of mean temperature, °C/cm
A_m = amplitude of temperature, °C
P = period, sec
t = time, sec
t_m = time of maximum, sec

A reference level of 2.5 ft, instead of the surface, was used for the prediction and all further computations. It was based on the fact that below this level the consistency and density of the soil was uniform, and also the measurable diurnal variation of temperature extends only to 2.0 ft. This method still satisfies the original boundary condition and eliminates the necessity of removing the diurnal variability from upper level data.

The temperatures at the reference level were based on data obtained by the Meteorology Group at their installation. An extremely conservative value of the thermal diffusivity was similarly obtained. By means of (2), calculations were made for 5, 10, and 20 ft to predict the annual extreme in temperature and were verified in the following manner.

One year of data, starting October 1954, for each of four stations are shown in Figures 4, 5, 6, and 7. All stations have a regular periodic pattern indicating decreasing amplitudes and phase with increasing depth. The analysis showed that the two open stations, north and east, have similar traces. Also, the two shaded stations, south and

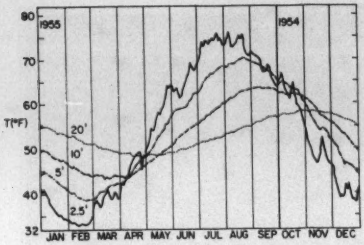

FIG. 4 – Soil temperatures, North station

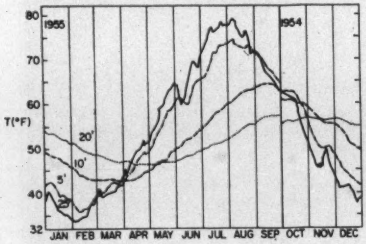

FIG. 5 – Soil temperatures, East station

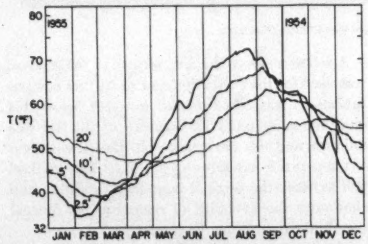

FIG. 6 – Soil temperatures, South station

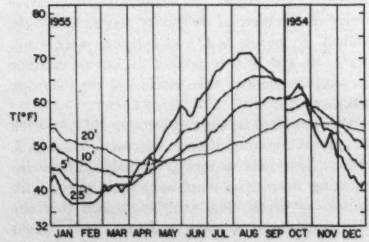

FIG. 7 – Soil temperatures, West station

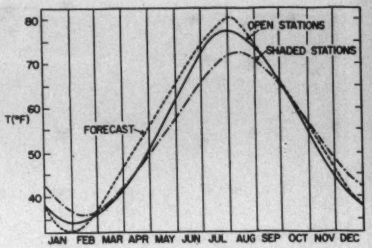

FIG. 8 – Average 2½-ft sub-soil temperatures

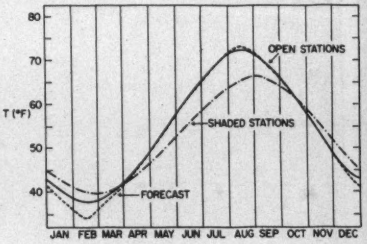

FIG. 9 – Average 5-ft sub-soil temperatures

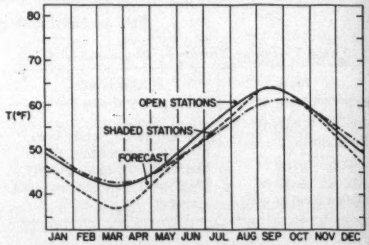

FIG. 10 – Average 10-ft sub-soil temperatures

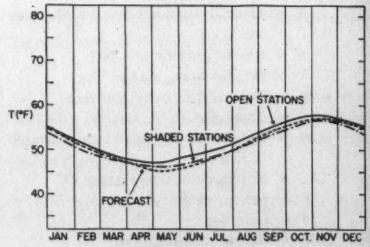

FIG. 11 – Average 20-ft sub-soil temperatures

west, are identical. A smooth curve of the average temperatures for the open and shaded satations are shown in Figures 8, 9, 10, and 11. As can be expected, the open stations have greater range and earlier maxima and minima than the shaded stations at all depths.

The predictions are also plotted on the previous figures. Based on an extremely large thermal diffusion coefficient which approximates granite rather than dry sand, the predicted temperatures were planned to be higher than the observed maxima and lower for the minima. As desired, the forecast had greater amplitudes to the depths of ten feet, but at 20 ft they both were equal, thus, indicating that the thermal diffusion coefficient was not too large.

Two methods are normally used to compute thermal diffusivities from (2). One method is by forming the ratio of temperature amplitudes at two different levels

$$A_{m_2}/A_{m_1} = \exp(z_1 - z_2)\sqrt{\pi/Pa} \qquad (3)$$

and the other method is by the relationship of the lag in time of the maximum temperature or minimum with depth.

$$t_{m_1} - t_{m_2} = (z_1 - z_2)\sqrt{P/4\pi a} \qquad (4)$$

The thermal diffusivities were computed by both methods using the average data shown in Figures 8–11 and are listed in Table 2.

TABLE 2 – *Thermal diffusivities* (cm^2/sec)

Depth	Amplitude method		Lag method	
	Open	Shaded	Open	Shaded
2.5– 5.0	0.019	0.007	0.009	0.009
2.5–10.0	0.012	0.014	0.009	0.009
2.5–20.0	0.015	0.019	0.012	0.012
5.0–10.0	0.010	0.021	0.009	0.009
5.0–20.0	0.015	0.024	0.013	0.013
10.0–20.0	0.019	0.026	0.016	0.016

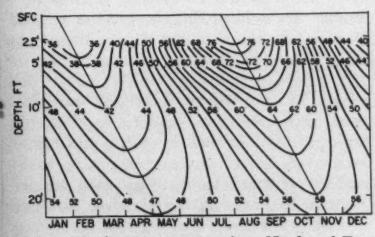

FIG. 12 – Isotherms at open stations, North and East

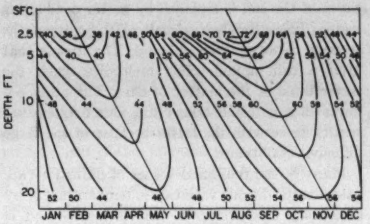

FIG. 13 – Isotherms at shaded stations, South and West

TABLE 3 – *Thermal diffusivity of various substances*

Substance	Thermal Diffusivity
	cm^2/sec
silver	1.72
iron	0.19
granite	0.021
ice	0.012
loam	0.0066
dry sandy soil	0.0013

The diffusivities obtained by the lag method are identical for both the open and shaded stations. No consistent relationship appears for the amplitude method. The diffusivities computed by the amplitude method are normally larger than the ones computed by the lag method. This indicates a deficiency of the theoretical model because it is based on a constant coefficient.

An average value of the diffusivity for the entire layer can be obtained by means of (4) which is an equation for a straight line. If the slope of the line indicating the time variation of the lag of temperature is known, it is possible to compute the diffusivity. In Figures 12, and 13, isotherms of subsoil temperature are drawn with the line of best fit indicating the lag of temperature with time. The average value obtained using either the maximum or minimum slopes produced a value of 0.013 cm^2/sec.

The small changes of diffusivity appear to be negligible. However, from a practical point of view, the equations are extremely sensitive and a small change in diffusivity produces a significant temperature change. Most of the coefficients we obtained are much larger than are customarily obtained for a dry sandy soil [*Geiger*, 1950, pp. 26–35, 138–152; *Landsberg*, 1944, pp. 103–108; *West*, 1952]. In fact, the values approach the diffusivity of granite as can be seen in Table 3.

The coefficient could be explained if our sandy soil retains a considerable amount of moisture. In other words the poorly conducting air in the

pores of the soil is replaced by better conducting water. There are two schools of thought on the seepage of water through sand. The first is that after a rain actual water molecules reach the water table in the matter of days. The other believes that it would take years. Our temperature results agree with the latter because of the large diffusivities obtained.

Many of the published values of diffusivity are based on the diurnal variation of temperature or by laboratory measurements. The latter method is completely satisfactory if one could obtain a representative sample of earth. The diurnal thermal diffusivities have been computed between two inches and one foot using data taken from the meteorological installation. The results indicate a large variation from 0.007 to 0.075 cm^2/sec. There are no consistent values and it is believed to be caused by the large variation of soil moisture and composition in the upper levels. In order to obtain a statistically significant diffusivity from the diurnal variation of sub-soil temperature, an extremely large sample is necessary.

Summary—To assist in the design of a new synchrotron, measurements of sub-soil temperatures were made at four locations to the depth of 20 ft. The analysis of one year of data showed that the difference in ground cover has an appreciable effect on the amplitude of temperature at all measuring depths [*Greene*, 1953]. Also, published standard thermal diffusion coefficients for a sandy soil are too small to account for the observed range of annual temperatures.

This project will continue after the structure has been completed. Measurements of the variation of temperature at several distances from a large sub-soil structure should produce data of interest.

Acknowledgments—The authors are indebted to the entire Meteorology Group for their assistance in the collection of data. Due credit should be given to M. E. Smith, Meteorology Group Leader, and J. H. Lancaster, Acceleration Development Department, for the various aspects of co-ordinating, planning and discussion concerning this project. This research was carried out under the auspices of the U. S. Atomic Energy Commission.

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A Study of Relative Erodibility of a Group of Mississippi Gully Soils

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Abstract—In attempting to correlate watershed characteristics with reservoir sediment in a 1951 study, unexplained variation was found. It was thought that basic differences in soil erodibility between watersheds might account for a part of this variation. Accordingly studies were made to determine erodibility difference between soils, using several methods and using gully soils, free of vegetative influences. No absolute measure of erodibility seemed available. A laboratory rainmaker was used on cores of undisturbed soil and compared with a wet sieving aggregate stability method on pulverized soil. Both were contrasted with natural rain splash losses on 9-inch diameter cores of undisturbed soil.

Soil losses by laboratory splash technique generally compared very well with results by the aggregate stability method. The results from these two methods did not compare well with splash erosion caused by 29 months of actual rain except from the sandy material. The high percentage of natural rain at intensities below the critical value for detaching cemented soils was thought responsible.

It appears that soils vary widely in their resistance to erosion as determined by any method. It further appears that relative erodibility may be varied depending upon the choice of methods of applying the erosion producing energy. Although no generally accepted standard method of assessing erodibility is yet available it is encouraging that different soils show widely different erosion rates. Therefore there is a possibility of deriving a method adequate to express erosion susceptibility differences. Loose sandy material from different geologic sources had about the same erosion potential regardless of method of evaluation. In general splash erosion increased with increase in sand content of the soil material. Aggregate stability decreased with increasing sand content.

Introduction—Sedimentation surveys were made on a group of 23 small reservoirs in north Mississippi early in 1951. An attempt was made to correlate watershed characteristics with reservoir sediment with somewhat erratic results [*Woodburn*, 1955]. Watershed characteristics considered were reservoir age, watershed area, watershed gross erosion rate, and reservoir capacity per square mile of drainage area. Owing to lack of erosion data, the same basic erosion rate was used for all watersheds in computing sheet erosion for addition to gully erosion to obtain the gross erosion rate. It was felt that there were other unconsidered variables influencing the reservoir sediment such as rainfall differences and perhaps soil erodibility differences between watersheds.

In selecting methods for measuring soil erodibility, a rather formidable problem was immediately presented as to type, rate, and total quantity of erosion-producing energy to be applied to the soil.

Erosion in general results from a complex interaction of detaching and transporting forces. Where long periods of time are available, small runoff plots under natural rainfall have given valuable data. Various supplemental studies have also been made using artificial rainfall on runoff plots in the field and in the laboratory. Artificial rainfall has been used to some extent for raindrop splash erosion investigations. Laboratory studies of aggregate stability and soil-dispersion rates have also been made to give an index of soil stability.

A review of methods for measurement of erodibility led to the conclusion that a standardized method of measuring soil erodibility is not available at this time. It was, therefore, decided that raindrop splash technique would be used with a small laboratory rain applicator to test the relative resistance of soil samples to detachment by drop action. Aggregate stability measurements were also made for samples of the same soils using the technique described by Byrant and others [1948] and by Slater [1951]. The laboratory results by both methods were compared with raindrop splash data from natural rains.

It was further decided that samples should be taken from gully areas only in this study of erodibility differences in soils. This eliminated the complicating factor of vegetative cover differences. Although the scope of this study was limited to gully soil materials, it was hoped that it would point the way to more extensive investigations of soil erodibility on a watershed basis.

Procedure—Undisturbed cores were taken from several gully sites, Table 1, by the method outlined by *Woodburn* and *Jones* [1946]. These cores, 3¼

TABLE 1 – *Splash erosion loss and Slater test stability percentage on some gully soils*

Location and soil	Volume weight	Erosion loss by splash		Mechanical analysis			Water stable aggregates, Slater method, duplicate tests	
				Sand >0.050 mm	Silt 0.050–0.002	Clay <0.002		
		gr	inch	pct	pct	pct	pct	pct
Tallahatta formation								
Berkeley Mitchell farm, gully 1E								
Top soil, silty clay	1.376	35.8	0.174	7.95	67.54	24.51	91.46	93.09
Cemented sand clay	1.710	104.6	0.409	68.13	15.31	16.56	9.16	15.85
Fairly loose, red sand	1.565	129.3	0.552	84.46	1.54	14.00	15.45	26.44
Berkeley Mitchell farm, gully 3W								
Very loose sand	1.441	139.9	0.649	89.83	3.59	6.58	3.20	9.61
Pontotoc Ridge, south								
Hobson place								
Very loose sand	1.585	151.1	0.638	92.52	3.78	3.70	...	...
Russell place								
Very loose sand	1.516	149.8	0.661	93.45	3.18	3.37	...	...
Warren Place								
Red sandy clay, Oct. 31, 1951	1.718	81.4	0.317	34.21	35.93	29.86	28.9	31.0
Red sandy clay, Nov. 9, 1951	1.696	74.1	0.292	34.21	35.93	29.86	Same	Same
Loose yellow sand, site 1	1.478	140.4	0.635	92.40	3.82	3.73	...	...
Loose yellow sand, site 2	1.475	134.7	0.611	91.06	5.09	3.85	...	...
Pontotoc Ridge, north								
Crumpton place								
Top soil, silty clay	1.642	69.4	0.283	39.82	30.77	29.41	53.00	52.15
Cemented, red sand four feet down	1.658	73.9	0.298	69.13	4.27	26.60	22.26	13.89
Cemented, red sand seven feet down	1.607	103.0	0.429	76.17	4.46	19.27	12.46	18.74
Sparta sand formation								
Carroll County gully, 2¾ mi nw of Carrollton								
Silty material, eight feet down	1.417	47.0	0.222	1.61	69.66	28.73	70.61	61.12
Mottled silt material	1.534	52.0	0.227	7.68	77.19	15.13	...	...
Hard red sand	1.788	123.4	0.461	79.40	3.39	17.21	2.82	3.22
Silty clay, near gully floor	1.572	76.8	0.327	19.26	61.47	19.27	34.11	34.52
Loose white sand	1.491	139.8	0.627	96.86	0.43	2.71	...	...
Sparta sand formation, Marshall County								
Top two inches	1.477	42.2	0.191	3.18	78.75	18.07	76.54	82.97
Silty clay gully rim	1.504	35.6	0.158	3.33	67.61	29.06	42.99	48.36
Hard silt six feet down	1.723	45.9	0.178	33.24	53.15	13.61	2.98	3.20
Red sand clay	1.671	112.8	0.451	75.56	7.02	17.42	5.13	6.08

inches in diameter and 2 inches deep, were removed to State College and there subjected to artificial rainfall by a technique described by *Woodburn* [1948]. Pre-run wetting by capillarity was employed so as to have the initial moisture content for each soil core at saturation. One hour of rain application at 6½ inches per hour was used on all cores of soil material studied. The amount of soil splashed out of the cylinder was determined for each sample. Erosion losses by splash as well as the physical properties of the soil cores are shown in Table 1.

Disturbed soil material from the same sites represented by the cylinders of undisturbed soil was air dried, graded 5 mm to 3 mm, and subjected to a wet sieving process as outlined by *Slater* [1951]. The percentage of the material remaining on a 0.5 mm sieve was noted as the percentage of water-stable aggregates larger than 0.5 mm (Table 1).

On nine of the 22 sites studied with the 3½-inch diameter cylinders, 9-inch diameter by 4-inch deep undisturbed cores were also taken and transported to State College and installed outdoors on the natural ground surface in a level position. Extreme care was necessary in obtaining undisturbed cores of the loose sand horizon both for the 9-inch cylinders and for the 3½-inch cylinders. These 9-inch soil cores were exposed to natural rainfall for the 29-month period from September 1951 to February 1954 (Table 2), in which 103.52 inches of rainfall occurred somewhat less than the long-time average. Splash loss by natural rainfall was determined at the end of the 29-month period on a weight basis and converted to inches.

TABLE 2 – *Splash erosion loss from cores of undisturbed gully soils of northern Mississippi exposed at State College, caused by 103.52 inches of natural rain during a 29-month period, September 1951 to February 1954*

Location and soil	Splash erosion loss[a]			Splash loss from 3½-inch dia. cores with laboratory rainmaker, one hour of rain 1951 tests	Relative erodibility determined by natural rains of 29-month, and by one hour of laboratory rain; very loose sand from Russell Place equals 1.00	
	Cylinder 1	Cylinder 2	Average		Natural rain losses divided by 1.885	Lab. rain losses divided by 0.661
	inch	inch	inch	inch		
Tallahatta formation						
Berkeley Mitchell farm, gulley 1E						
(a) Top soil, silty clay	1.52	1.55	1.535	0.174	0.81	0.26
(b) Cemented sand clay	0.93	0.75	0.840	0.409	0.44	0.62
(c) Fairly loose red sand	1.31	1.28	1.295	0.552	0.70	0.83
Berkeley Mitchell farm, gully 3W						
(d) Very loose sand	1.83	1.54	1.685	0.649	0.88	0.98
Pontotoc Ridge, south						
Hobson place						
(a) Very loose sand	1.91	1.65	1.780	0.638	0.94	0.96
Russell place						
(b) Very loose sand	2.06	1.71	1.885	0.661	1.00	1.00
Pontotoc Ridge, north						
Crumpton place						
(a) Top soil, silty clay	1.14	...	1.14	0.283	0.60	0.43
(b) Cemented red sand four feet down	1.47	1.35	1.41	0.298	0.75	0.45
(c) Cemented red sand seven feet down	1.33	1.40	1.365	0.429	0.72	0.65
Cups of washed sand, 3½-inch diameter, exposed to natural rain as shown						
Sand graded 50–70 mesh, 103.52 inches rainfall	3.69	3.64				
Sand graded 50–70 mesh, 100.57 inches rainfall	3.24	3.36				
Sand graded 60–70 mesh, 100.57 inches rainfall	3.43	3.36				

[a] Nine-inch diameter cylinders four inches deep, natural soil structure, 29-month period of natural rain.

Discussion of results—Reference to Table 1 will disclose a rather wide difference in the susceptibility of the various cores of gully materials to erosion. Hard silts and silty clays were more resistant to erosion, suffering a loss of only 0.16 to 0.17 inch under the standard rain application. Cores of loose sandy material suffered the highest splash loss of 0.60 to 0.65 inch.

Splash erosion loss was plotted against the percentage of sand in the soil cores (Fig. 1), and a rather pronounced trend is apparent. Perhaps of considerable significance is the nearly constant erosion rate for the sandy material from the gullies regardless of the geologic formation and location. This sandy material is the source of the most of the damaging sediment produced in the Yazoo basin in Mississippi. In Table 1 the percentage of water-stable aggregates remaining after wet sieving is shown. Aggregate stability tests could not be made on the samples of highest sand content, that is above 90 pct sand. When this material was pulverized by the standard method, nothing was retained on the 0.5 mm sieve even before the sieve nest was placed in water. When pulverized to

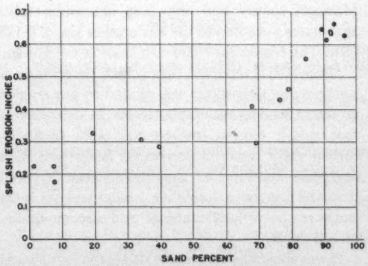

FIG. 1 – Relationship of sand percentage and splash erosion for some Mississippi gully soils

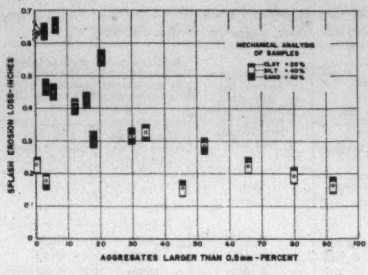

FIG. 2 – Relationship of aggregate stability and splash erosion for some Mississippi gully soils

pass five mm, the material fragmented on down to virtual sand grain size and passed through the three mm sieve.

In figure 2 splash erosion loss is plotted against percentage of water-stable aggregates. A fairly consistent downward trend in splash erosion loss is shown as percentage of water-stable aggregates increases. The samples of high sand content with little or no water-stable aggregate properties suffered the greatest splash erosion. Material with a binding material such as silt and clay in sufficient quantities showed least splash erosion. Although a generally satisfactory correlation was observed between splash erosion and aggregate stability, two outstanding exceptions were noted. Mottled silt material from Carroll county had no water-stable aggregates yet had only 0.277 inches of erosion loss. Hard silt material below six feet from Marshall county had only 2.98 pct water-stable aggregates yet suffered the low erosion loss of 0.178 inch. The reason for these two cases is not known.

Slater [1951] reported that a high percentage of water-stable aggregates was related to low erosion as determined by runoff plot losses. It is of interest that splash erosion loss on the cores of undisturbed gully material correlated fairly well with aggregate stability. It should be borne in mind that the aggregate stability measurements were made on pulverized material and not on undisturbed cores.

It was shown by *Woodburn* [1948] that structural condition of a soil, that is whether undisturbed or pulverized, drastically affected the magnitude of erosion loss by raindrop splash. All soils tested in the 1948 study were shown to be far more susceptible to raindrop splash when pulverized than as undisturbed cores. In general, those soils most susceptible to splash erosion in the undisturbed state were also most erodible in the pulverized state. A notable exception was Memphis silt loam which when pulverized behaved as a superfine sand of great vulnerability to splash erosion.

In the application of the results of the 1948 study to field problems, the matter of soil physical condition is of great importance. For example, freezing and thawing of a gully wall will create a layer perhaps an inch thick which is loose and virtually pulverized, far different from the original solid structure of the soil. All evidence indicates that a given unit of rainfall energy will remove a great deal more of the pulverized than of the undisturbed material.

Splash losses caused by 29 months of natural rain on nine-inch cores of nine of the materials previously mentioned are shown in Table 2.

Cores of loose sandy material suffered greatest erosion loss. This followed the same trend shown for these materials in 3½-inch cores with the simulated rain in the laboratory.

In calculating relative erodibility of the materials for the natural rains series of test, the Pontotoc Ridge, Russell place, very loose sand, suffering 1.885 inches of loss, was taken as unity. The losses for the other samples were divided by 1.885 to secure relative losses with respect to the highest. The same was done for the laboratory rain applicator losses from the 3½-inch cores in that the same material was highest with 0.66 inch.

Relative erodibility for the high sand materials corresponded very well for the two methods. There was wide divergence, however, for the other materials.

It is believed that cohesive soils with sufficient clay and silt binder may be expected to show erratic splash erosion results with natural rains. Much of the natural rain may be of low erosion-producing power on account of small drop size or low intensity. It may be below the minimum necessary to cause detachment and a breakdown of structure yet adequate to remove loose or sandy material.

A study of four years of rainfall at State College, Mississippi for the period January 1946 to January 1950 indicated that 41.4 pct of the rain occurred at an intensity of less than 0.19 inch per hour. In the 2036 hours of rainfall during the period 82.6 pct was at an intensity of less than 0.59 inch per hour. Only 5.91 pct was at a rate of 1.00 inch per hour or more.

Cups (3½-inch diameter) of washed and graded sand lost almost twice as much as the cores of

sandy gully material. This was partially because these cups were periodically filled and the level was kept near the top of the cup. There was therefore little effect of the side of the container in intercepting any splashed material. Since the sand was graded between narrow limits, there was little grain interlocking to reduce splash. The smaller diameter cup undoubtedly also allowed increased amount of splash.

It was reported by *Woodburn* [1949] that a gully similar to the Berkeley Mitchell site reported herein lost soil at the average rate of nearly two inches per year from 1939 to 1949. This gully contained a small area of the silty top soil, a considerable amount of the cemented hard red sand or sandy clay and a fair percentage of the area consisted of the loose red sand. The two-inch rate would represent an overall summation of the rates of the various soil material. In any event, it is greater than even the 29-month splash loss from the nine-inch cylinders of the loose sandy material. The 29-month period should be considered as about two years by virtue of the actual rainfall received. In a typical gully site, the average soil slopes would be of the order of 45°; therefore splash erosion would be far more effective in removing soil than on the level surface of the cylinders set up at State College. Even for the short gully slopes, there would also be a small amount of runoff erosion to add to the splash losses. Freezing and thawing during the winter period would also increase splash erosion loss on natural gully walls due to some pulverizing and loosening of the normally monolithic material. It, therefore, seems logical to conclude that two years of normal rainfall would not cause as much splash erosion on soil cores placed in a level position as would occur in two years on typical gully slopes.

Summary and conclusions—Cores (3¼-inch diameter) of gully soil from several sites in natural structural condition were exposed to splash erosion caused by a small laboratory rain applicator. The same material in a pulverized state was tested for aggregate stability by the *Slater* [1951] method. Nine-inch diameter cores of the same gully soils were exposed to 29 months of natural rainfall.

The small cores lost from 0.17 inch to 0.66 inch under 6¼-inches rain in one hour. The loose sandy material had about the same splash erosion value regardless of its geologic source. Splash erosion loss was rather well correlated with sand percentage.

The gully soil materials varied widely in their aggregate stability with the high sands having virtually no stable aggregates. High aggregate stability was rather well correlated with low splash erosion while the materials of low aggregate stability suffered high splash erosion losses.

Nine-inch diameter cores subjected to natural rains also showed a wide difference in their susceptibility to splash loss. The high sands suffered most as they did in the laboratory test; however, relative erodibility by the two methods was not well correlated. Splash erosion losses from the nine-inch cores under natural rainfall were less than actual gully erosion losses from long time measurements.

There is a wide difference between soil materials in their resistance to erosion forces. Relative erodibility may be determined but the results may be influenced by the method of preparing the soil and applying raindrop energy. A measure of absolute erodibility does not seem available at this time.

Some difficulty will always be present in comparing several watersheds as to their basic erosion rate. It is encouraging, however, that rather wide differences in erodibility between various soil materials are reported in this study. Some promise is given that composite watershed erosion rates may be developed on the basis of amount and erodibility of the various soils present.

Acknowledgments—J. B. Burford, Hydraulic Engineer assigned to this project 1951 to 1954 performed or assisted in performing many of the tests reported in this study.

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Channel *P* Waves Π*g* in the Earth's Crust*

F. Press and B. Gutenberg

Abstract—The prominence on seismograms of channel *S* waves (*Lg*) suggests the existence of the corresponding longitudinal wave (Π*g*). Examination of seismograms from North American stations for the Kern County earthquake of 1952 revealed the existence of this phase. It is characterized by small amplitude and erratic occurrence. The weakness of Π*g* in contrast to the great strength of *Lg* is interpreted in terms of propagation in a crustal channel bounded on top by the Earth's surface.

Introduction—Channel *S* waves in the continental crust are well established and have been given the symbol *Lg*. Usually they are characterized by large amplitudes compared to *P* or *S*, and occur with periods in the range three to eight seconds. They have not been observed for paths under deep oceans, but propagate efficiently through the continental crust. The existence of *Lg* raises the question of the corresponding longitudinal wave which we propose to call Π*g*.

Observations of Π*g*—After *Gutenberg* [1951] suggested that the $\overline{P}$ group at short distances corresponds to Π*g*, *Båth* [1954] and *Gutenberg* [1955] attempted to find the Π*g* phase on seismograms of teleseisms. Although some indications of the phase were found they concluded that it was either small or absent. In this paper we report the results of a search for Π*g* on seismograms of the Kern County earthquake of 21 July 52, 11h52m14s. The existence of the phase was established; however, its occurrence was erratic and the amplitudes $\Pi g/P$ were much smaller than Lg/S. It is probable that Π*g* would not have been reported had it not been expected from its *Lg* analogue. However, when the seismograms were read independently by both authors the same phase was selected as Π*g*. The possibility that these observations result from an aftershock is excluded by the apparent velocity of the waves.

Table 1 lists the data. Given are the distances, travel times, velocities of Π*g*. There is some doubt as to the distance where Π*g* begins and the *P*-group ends. It is therefore uncertain whether the first four listings in Table 1 correspond to the data for greater distances. Of a total of nineteen stations between 18° and 38° for which the path was entirely continental and records were available, only on the seismograms of eleven stations was an indication of Π*g* found. The mean velocity of Π*g* for these stations was 6.09 ± 0.06 km/sec. In contrast all nineteen stations recorded *Lg*. The best examples of seismograms showing Π*g* are given in Figure 1.

Discussion—The erratic behavior of Π*g* is partly related to its small amplitude and partly to the varying amplitudes occurring in the seismograms between *P* and *S* from other types of waves. Thus we are faced with the problem of picking the small Π*g* phase in a background of irregular motion.

TABLE 1 – Π*g* *Travel time data*

Station	Δ	Π*g* travel time	Velocity
	°	sec	km/sec
Ukiah	5.28	97	6.05
Ferndale	6.93	130	5.92
Butte	12.05	217	6.17
Alberni	14.89	263	6.27
Lincoln	18.61	344	6.01
Guadalajara	19.85	345	6.39
Tacubaya	23.45	438	5.95
Pueblo	24.40	467	5.81
Chicago	25.4	482	5.86
Merida	29.4	522	6.26
Columbia	31.2	558	6.21
Kirkland Lake	31.7	565	6.23
Ottawa	34.3	641	5.94
Palisades	35.7	657	6.04
Weston	37.5	667	6.25

The weakness of Π*g* cannot be explained in terms of excitation at the source. This follows from the observation that near the source the amplitude ratio $\overline{P}/\overline{S}$ is much larger than that of $\Pi g/Lg$ at greater distance. Moreover, *P* and *S* amplitudes are of the same order at these larger distances. We must, therefore, look to effects of propagation to explain the weakness of Π*g*.

The velocity data show some scatter, which is partly due to the uncertainty in finding the beginning of the phase. The average velocity of about 6.1 km/sec is slightly smaller than that of *P* waves below the sedimentary layers of the crust as ob-

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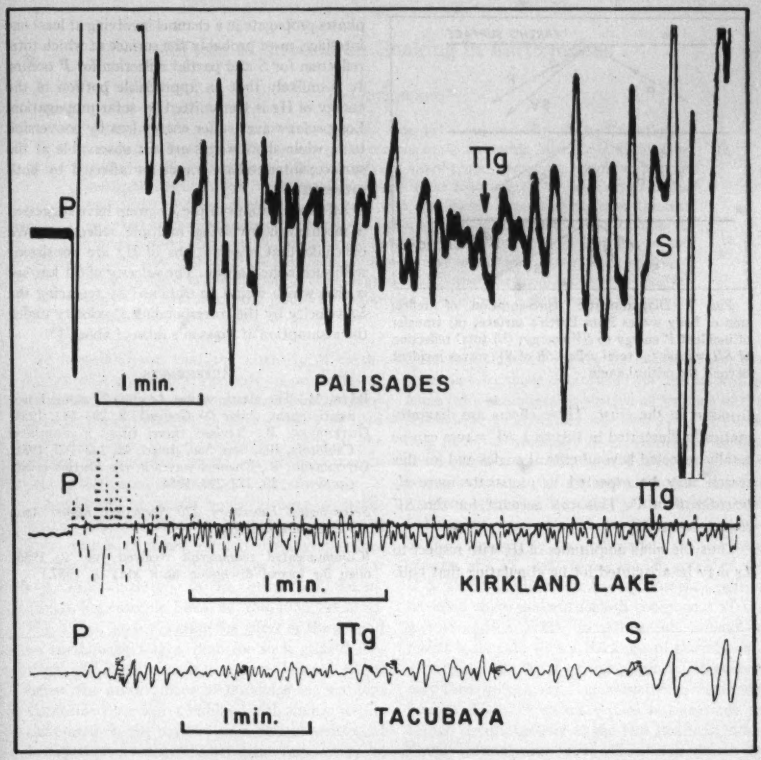

FIG. 1 – Examples of the Πg phase from the Kern County earthquake of 1952 recorded at Palisades, Kirkland Lake and Tacubaya

served in blasts. It corresponds approximately to the velocity of the beginning of the $\overline{P}$-group in near earthquakes [*Gutenberg*, 1951].

Suggested mechanism—The mechanism of propagation of Πg must account for its velocity and small amplitudes. Transmission of a compressional wave in the crust to large distances requires propagation through a channel. The specifications of such a channel can be quite broad. For example, curvature of the Earth, velocity changes with depth, interfaces between layers may act to form channels by guiding body waves along paths involving multiple reflections or by confining rays to a channel by bending of the ray in the regions of velocity gradient above and below the axis of low velocity. A combination of both is possible. In order for long distance propagation to occur, no appreciable amount of energy must leak out of the channel. We infer that the weakness of Πg relative to *Lg* suggests a relatively greater leakage for Πg. The velocity of *Lg* is less than or equal to the velocity of body waves near the channel. The velocity of Πg exceeds that of shear waves in or near the channel, hence, energy may leak out of the Πg channel as *S* waves. To be more specific it is well known that *SH* waves, which are the predominant constituent of *Lg*, are totally reflected from a free surface. On the other hand, as *Båth* [1954] points out, Πg as all longitudinal waves, loses energy by conversion to *S* at discontinuities which are likely

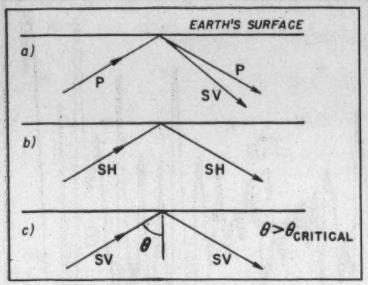

FIG. 2 – Diagrammatic representation of reflection of body waves from Earth's surface; (a) transfer of incident P energy to SV energy; (b) total reflection of SH waves; (c) total reflection of SV waves incident beyond the critical angle

to occur in the crust. These effects are diagrammatically illustrated in Figure 2. SV waves can be totally reflected beyond critical angles and for this reason may be expected to propagate more efficiently than P. This can account for the SV component of Lg.

Thus the small amplitudes of Πg with respect to Lg may be accounted for by stipulating that both phases propagate in a channel involving at least one interface, most probably the surface at which total reflection for S and partial reflection for P occurs. It is unlikely that an appreciable portion of the energy of Πg is transmitted by sofar propagation. Long sofar waves suffer energy loss by conversion to S, while short waves are not observable at the surface; intermediate waves are affected by both processes.

All investigations of the Lg group have suggested a mechanism involving multiple reflections. We conclude that observations of Πg are consistent with such a mechanism. The velocity of 6.1 km/sec is that which would be obtained by replacing the Lg velocity by the corresponding P velocity under the assumption of Poisson's ratio of about $\frac{1}{4}$.

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Effects of Ground on Shaking in Earthquakes

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Abstract—Records of nearby earthquakes recorded simultaneously at the Seismological Laboratory, located on granite, and on the campus of the California Institute of Technology, located on alluvium, show that the first wave of a new phase frequently records with rather small differences at the two stations; however, if the following waves had periods of less than about two seconds they were recorded with appreciably larger amplitudes on the campus than at the Seismological Laboratory. Large amplitudes continued on the campus appreciably longer than at the Seismological Laboratory. Data available for locations on poor ground show that there the maximum amplitudes may be as much as ten times as large as those recorded at the Seismological Laboratory under otherwise equal conditions. Considering the importance of such results for engineering seismology it is intended to continue this research on a larger scale.

It is well known that the intensity of earthquakes at a given point depends on properties of the ground, and 'ground-factors' have been assigned to seismological stations at least as early as 1914 [*Gutenberg* 1924, p. 53]. However, effects of the ground on recorded elastic waves have rarely been investigated in detail.

Amplitudes of elastic waves in near-by earthquakes and accelerations have been calculated from records of strong motion seismographs and published annually since 1933 by the U. S. Coast and Geodetic Survey in the series U. S. Earthquakes (for example, Serial no. 755, 1952; Serial no. 773, 1954). To investigate the effect of the ground on earthquake waves, data for such ground motions obtained from instruments located at or below the ground floor of buildings in Southern California have been combined with similar results calculated on the basis of seismograms written at installations of the Seismological Laboratory of the California Institute of Technology (CIT). Accelerographs of the U. S. Coast and Geodetic Survey are installed mainly in city buildings to get information on ground motion and acceleration under various conditions and to serve engineers as basis for the design of earthquake resistant structures. All are on recent deposits, usually alluvial. On the other hand, whenever possible, the stations of the Seismological Laboratory have been constructed on solid rock to get a minimum distortion of the arriving waves by surface layers.

During an investigation of the energy of earthquakes *Gutenberg* and *Richter* [1956] found that for a given earthquake, the average ratio of the largest ground amplitudes reported by the U. S. Coast and Geodetic Survey for locations near the epicenters to those determined for the same distance from seismograms written at stations of the Seismological Laboratory was near 2½:1. To check this ratio, a standard Wood-Anderson torsion seismograph with constants known from tests before and after the experiment to be identical with one operating in routine at the Seismological Laboratory was installed on February 1, 1955, in the basement of the Athenaeum on the main campus of CIT, next to an accelerograph of the U. S. Coast and Geodetic Survey. For six weeks, it recorded there the north-south component of the ground motion. While the Athenaeum is built on recent sediments with a thickness of the alluvium of roughly 900 ft, the Seismological Laboratory, only three miles away, is constructed on weathered granite. Figure 1 shows typical seismograms recorded simultaneously at the two locations. Additional seismograms have been reproduced by *Gutenberg* and *Richter* [1956, p. 123]. The average maxima of waves with periods of about 0.2 to 1½ sec recorded in near-by earthquakes at the two stations show a ratio of about 4:1 [*Gutenberg* and *Richter*, 1956, pp. 112, 123]. This agrees within the limits of error with the ratio of roughly 3:1 between similar maxima of ground motion in eight larger shocks recorded during the past ten years simultaneously by the accelerograph of the U. S. Coast and Geodetic Survey at the Athenaeum and the torsion seismographs at the Seismological Laboratory.

For a comparison of the maximum amplitudes of ground motion with periods of the order of magnitude of one second in near-by earthquakes in Southern California the maximum motion at the Seismological Laboratory is taken as unity. Approximate corresponding maximum ground

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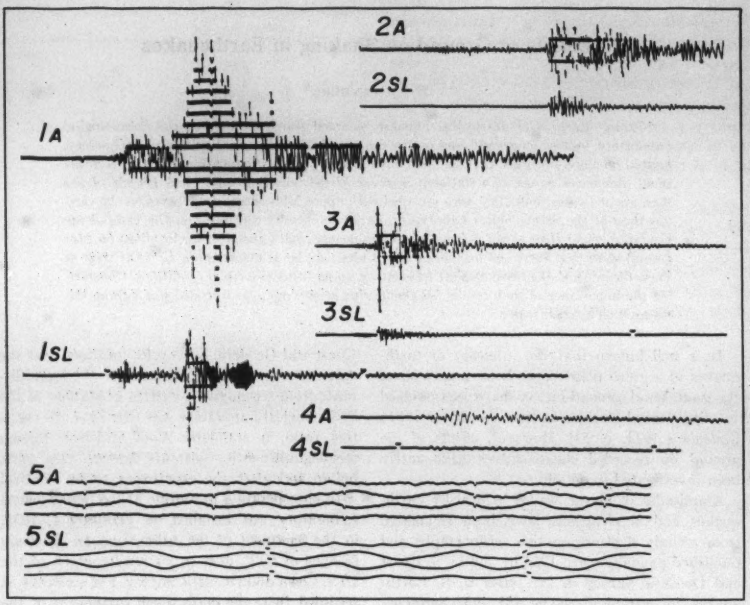

FIG. 1 – Seismograms of shocks recorded by identical instruments, *A* at the Athenaeum on the main campus of the California Institute of Technology, Pasadena (time marks every 30 sec), *SL* at the Seismological Laboratory (marks every minute); successive lines of each record are 15 minutes apart; dates, magnitudes *M*, and approximate distances Δ: (1) Feb. 11, 1955, $M = 4.5$, $\Delta = 140$ km; (2) Feb. 18, 1955, $M = 4.7$, $\Delta = 300$ km; (3) March 14, 1955, $M = 3.3$, $\Delta = 60$ km; (4) March 14, 1955, focal depth about 100 km, $M = 6\frac{1}{2}$, $\Delta = 4900$ km; (5) Feb. 27, 1955, $M = 7\frac{3}{4}\pm$, $\Delta = 9200$ km

amplitudes at stations of the CIT group under otherwise equal conditions (especially distance) are given in Table 1. Records written by accelographs of the U. S. Coast and Geodetic Survey, all on alluvium, give approximately the corresponding maximum ground amplitudes listed in Table 2.

A study of the seismograms written simultaneously by a torsion seismograph on the campus and one at the Seismological Laboratory shows that the first wave of a new phase, especially in case of impulses, frequently records with rather small differences at the two stations; however, if the following waves had periods of less than about two seconds (that is, in all near-by earthquakes) they were recorded with appreciably larger amplitudes at the campus than at the Seismological Laboratory (compare Fig. 1). The ratio of the amplitudes recorded at two locations can be expected to depend on such variables as the distance of the shock, the type of wave (for example, direct longitudinal waves, abbreviated by P, or transverse, abbreviated by S, or surface waves), the angle under which the waves of the P- and S-types arrive from the interior of the Earth, the duration of the shaking (which depends, among other factors, on the magnitude of the shock), and the period of the waves (which depends on processes near the source, the distance which the waves have traveled and the magnitude of the shock).

Table 3 shows characteristic data based on records of three distant earthquakes, one from a source in Alaska, one from a source at a depth of about 100 km in the Aleutian Islands (beginning reproduced in Fig. 1, no. 4), and one from a shock in the South Pacific (S-group in first line, surface waves in following lines of Figure 1, no. 5).

In records of nine shocks which occurred at distances of between 40 and 350 km (about 25 to 220 mi) from Pasadena and had magnitudes between about 3 and 5, the ratios listed in Table 4

TABLE 1 – *Relative maximum ground amplitudes a of waves with periods of 0.2 to 1½ sec in near-by earthquakes, recorded at stations of the Seismological Laboratory at Pasadena; amplitudes at the Seismological Laboratory are taken as unity*

Station	Ground	a
Pasadena (Seismological Laboratory)	Granitic rock	1
Riverside (Quarry south of Fairmont Park)	Granitic rock	1
Mount Wilson (Observatory)	Granitic rock	1½
Woody (N. E. of Bakersfield)	Granitic rock	2
Barrett Dam (near Mexican border)	Granitic rock	2½
Tinemaha (Owens Valley, Aqueduct)	Basalt	2½
Haiwee (Owens Valley, Aqueduct)	Loosely cemented tuff	1½
La Jolla (Scripps Inst. of Oceanography)	Consolidated detrital material	1½
Santa Barbara (Museum)	Alluvium with boulders	2½

TABLE 2 – *Relative maximum ground amplitudes a recorded by accelerographs of the U. S. Coast and Geodetic Survey, all on alluvium; unity and details as in Table 1; in parentheses, locations during at least the majority of the observations*

Location	a
Pasadena (California Institute of Technology Campus)	3½
Colton (Pac. Gas and Elec. Sub-station)	3
El Centro (Nevada-California Power Co.)	8
Bishop (Los Angeles Water Dept., Garage)	8
Hollywood (Storage Co.)	3
Long Beach (Public Utilities Bldg.)	2½
Los Angeles (Occidental Life Bldg; Subway Terminal)	4
Hollister (Library)	6
Westwood (Univ. of California at Los Angeles)	3
San Diego (Consolidated Gas and Electric Co.)	4
Vernon (C. M. D. Bldg.)	6
San Jose (Bank of America)	2
San Francisco (S. Pacific Bldg.; Alexander Bldg.)	3
Santa Barbara (Court House)	5
Taft (Lincoln School)	6
Oakland (City Hall)	2½

were found for waves in the transverse (S) group which includes at those distances the largest ground amplitudes. Relatively small ratios in the second line of Table 4 refer frequently to the first wave of a new phase, especially in case of impulses, larger ratios to later waves, starting usually with the second or third wave after the onset of a new phase. Most periods of corresponding waves are the same at the two locations within the limits of error of 0.1 or 0.2 second; the average difference is nearly zero. However, relatively strong shaking

TABLE 3 – *Average approximate ratio of amplitudes on the CIT campus to those at the Seismological Laboratory (SL) in corresponding waves of three distant earthquakes*

Wave length, km	5	10	15	20	30	40
Ratio CIT/SL	8	6	3	2	1¼	1
Range of ratio	2–14	2–11	1–8	1½–2½	1–1½	1–1½
Period of P, sec (approx.)	1	1½	2–2½	3	4	5
Period of S, sec (approx.)	1½	3	4	5	7	10

TABLE 4 – *Average approximate ratio of amplitudes, similar to Table 1, in the transverse wave group in earthquakes with epicentral distances between 40 and 350 km from Pasadena*

Wave length, km	1	1½	2	3
Ratio CIT/SL, range	1½–20	1–20	2–13	1–9
Average period, sec. (approx.)	¼	½	¾	1

continues on the campus a few times as long as at the Seismological Laboratory (see Fig. 1 and 2). Thus, the fact that repeatedly earthquakes have been felt on the campus of CIT but not at the Seismological Laboratory [*Gutenberg* and *Richter*, 1956, p. 122] results not only from larger amplitudes on the campus but also from longer continuation of strong shaking.

The results discussed in the preceding paragraphs are limited in various respects. First, they concern comparisons between the ground motion at only two locations, one on about average ground (the CIT campus) and one on good ground. It can only be guessed what might happen on poor ground (for example, artificial fills or alluvium with the water table near the surface), where from our scanty data the largest amplitudes may well exceed ten times those on good ground. Furthermore, maxima of waves with periods of over 1½ sec are recorded with relatively small magnification by accelerographs as well as standard torsion seismographs. Such waves may have relatively large amplitudes in major earthquakes and should be investigated separately; however, extrapolation from records of shocks up to magnitude 7 written in the epicentral area indicates that near the epicenter of a major earthquake the periods of the waves with the greatest acceleration are roughly one second on average ground [*Gutenberg* and *Richter*, 1956]. Moreover, no records of shocks with even slight damage locally are available thus far for comparison, although some of the shocks for which records have been obtained at both locations have been felt locally.

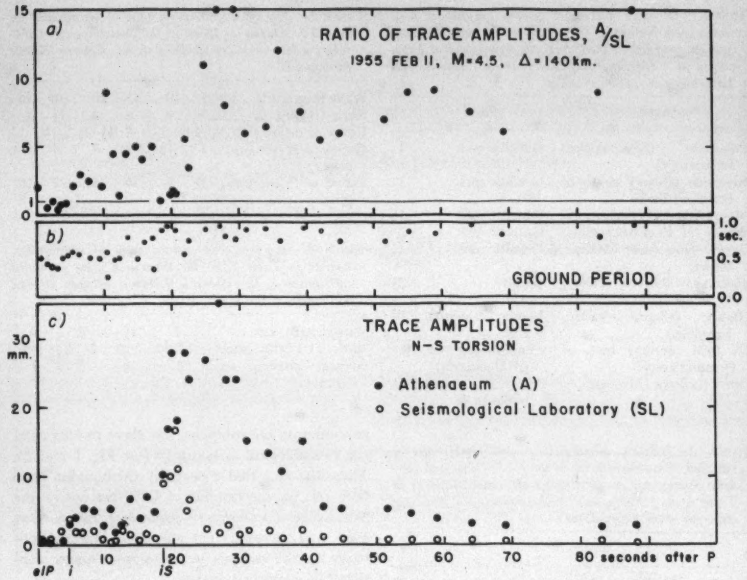

FIG. 2 – (a) Ratio of amplitudes at Athenaeum (A) on campus of *CIT* to those at the Seismological Laboratory (*SL*) for Kern County earthquake, Feb. 11, 1955, 19h; (b) corresponding average wave periods; (c) corresponding trace amplitudes

All results of this kind are not only of interest for investigation of waves and vibrations in general, but they are also of importance to engineering seismology and they affect discussion of such problems as risk of earthquake damage at a given location or minimum requirements for safety codes.

The present paper is intended as the first of a series of investigations to find effects of the ground on shaking. In applying results of this kind to specific earthquakes other elements affecting amplitudes have to be considered such as wave paths, type of the waves, effects of crustal structures. To find accelerations which, with certain limitations, are considered to have simple functional relations to the destructiveness, the periods have to be studied in more detail. However, such problems are outside the scope of the present research. Investigation of effects of the ground at locations separated by short distances must be continued on a larger scale before a study of the more complicated problems mentioned above can be started.

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Correlation of Some Igneous Rocks of New Mexico by the Fusion Method

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Abstract—Thirty-six samples of igneous rocks and ten of metamorphic rocks, for which complete chemical analyses have been obtained, were powdered and fused into artificial glasses in the carbon arc of a spectrograph. Curves showing the relation between the indices of refraction of such glasses and the composition of the rock samples may be used to estimate the approximate composition and may aid in the correlation of igneous rocks. By this method, the SiO_2 content of an unknown rock sample may be estimated to within three per cent of accuracy, whereas MgO, CaO, and the combined Fe_2O_3 + FeO may be estimated to within two per cent of accuracy. The method is not so satisfactorily applied to rhyolite and quartz latite, because these rocks do not readily form homogeneous glasses in the carbon arc.

Aside from the effect of changing proportions of SiO_2, the indices of refraction of the artificial glasses are determined, in decreasing order, by the oxides Fe_2O_3, TiO_2, FeO, MgO, CaO, Na_2O, and K_2O.

From comparative studies of variation diagrams, it can be shown why the method is particularly effective for volcanic rocks of intermediate composition, but may not be applied satisfactorily to altered, metamorphic, or other igneous rocks.

Introduction—Volcanic rocks are widespread in New Mexico and in places the correlation of units or groups becomes important to mineral exploration. The identification and correlation of such rocks, especially the fine-grained or glassy types, have been difficult both in the field and in the laboratory. Identification of such rocks by use of thin sections is also difficult, as many of these rocks contain a large proportion of fine-grained or glassy groundmass. Complete chemical analysis is a convincing method, but is very expensive. In view of the limitations of other methods, we have tried the fusion method and found it to be satisfactory for determination of approximate chemical composition of intermediate volcanic rocks.

The relations between the composition and index of refraction of natural glasses has been discussed in the last fifty years by *Tesch* [1903], *Tilley* [1922], *George* [1924], and many others. Silica has been the chief constituent to be estimated from determination of the index of refraction of the glass. However, the first comprehensive discussion of the relation between the composition and index of refraction of artificial glass made from rock sample was given by *Mathews* [1951]. We call Mathews' "useful method," the fusion method.

The fusion method may be defined as follows. The composition of a rock determined from chemical analysis is plotted against the index of refraction of a wholly fused sample of the same rock. When such points are plotted for the full range of chemical composition from basic to silicic for a sample, a curve can be drawn to which the index of refraction of an unknown rock can be compared and the approximate composition estimated.

Laboratory method—Each rock sample, about 20 gm, was pulverized to below 50 mesh with tool-steel mortar and pestle, and then powdered to below 200 mesh with agate mortar and pestle. The artificial glass was formed by fusing the powdered rock in the carbon arc of a spectrograph. Spectrographical-grade graphite electrodes, 8 mm in diameter were used. A small crater 2 mm in diameter, and 2 mm deep was carved out of the lower electrode, or the anode. This end of the electrode was tapered until the rim of the crater was about 0.5 mm wide. This crater is about 0.006 ml in size and held about 0.017 gm of the powdered rock of average density 2.78. The powder was moderately tightly packed in the crater with a spatula. A direct current of seven amperes and 50 volts was employed. The rock powder was fused for 30 seconds, then the electrode was removed from the spectrograph and cooled in room temperature. The glass bead was removed from the crater and crushed into angular grains of approximately 100 mesh for use in the determination of its index of refraction by immersion method. Reference curves (Fig. 1 and 2) of the index of refraction versus the percentage of silica and other oxides were plotted based on analytical and fusion data obtained from 36 volcanic rocks.

Accuracy of the fusion method—It has been found that the SiO_2 content of an unknown rock can be estimated to within three per cent, and the MgO, CaO, and the combined Fe_2O_3 + FeO may be

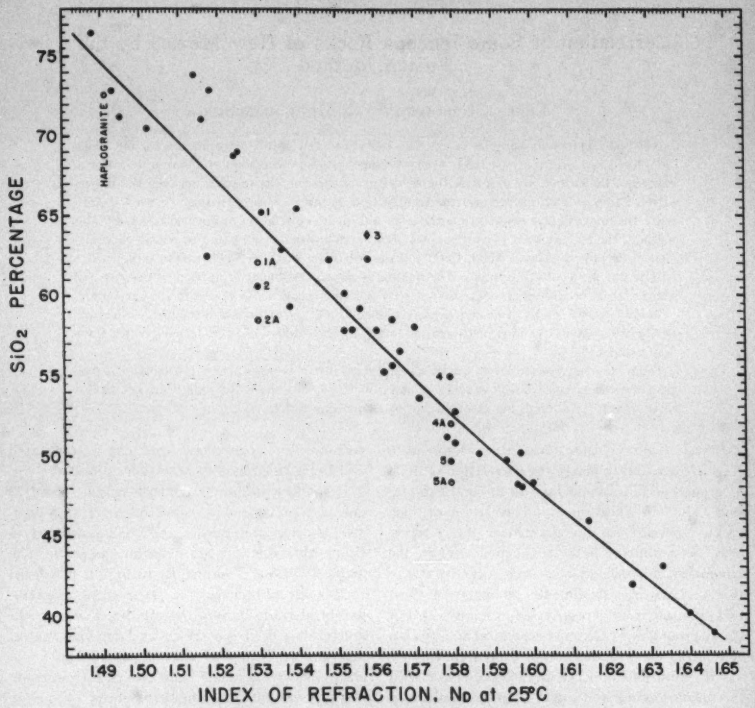

FIG. 1. – Curve shows the relation between index of refraction and the percentages of silica, based on analyzed samples of some volcanic rocks of New Mexico

estimated to within two per cent of accuracy. There are several reasons why this method is not completely definitive.

(1) From the result of all the fused samples we find that sometime only a portion of the powdered rock in the carbon arc is fused into glass. This is especially true for powdered rock samples of rhyolite or quartz latite, which have high silica content and are difficult to fuse into glasses of homogeneous composition. The glass will be badly contaminated with graphite particles by prolonged fusion. The determination of index of refraction of glasses made of acidic rock samples may be off by 0.01. This does not mean that one cannot fuse a homogeneous glass of rhyolite or granite by using other methods. For instance, Schairer [*Fairbairn* and *Schairer*, 1952] fused batches of haplogranite, and optical examination of the final glass showed a uniform index of refraction of 1.491. The silica content of the haplogranite is 72.64 pct. On the other hand, samples of basic volcanic rocks readily lend themselves to formation of homogeneous glasses. The indices of refraction of such glasses can be determined to within 0.002. The fusion experiment does not include alkalic or monomineralic rocks.

(2) Some artificial glasses, although completely fused in the carbon arc, may not have uniform density and therefore their indices of refraction may not be uniform. The glass is not annealed before the determination of the index of refraction. So, the indices of refraction of these glasses may vary as much as 0.003. Occasionally the glass is partly anistropic because of internal stress. Annealing may eliminate such internal stress, but it is

easier to fuse another sample so far as the time, equipment, and the purpose of the fusion method are concerned.

The density of silicate glass can be calculated from its composition by using the equations derived by *Huggins* [1940a]. However, there is discrepancy between the calculated and measured density. This discrepancy varies according to the composition range of the glass. When there is variation of seven major constituents in the silicate glasses made of igneous rocks, the discrepancy between calculated and measured density in different composition range may vary irregularly. Therefore, it is reasonable to believe that there is an irregular variation of index of refraction in different composition range of the silicate glasses.

(3) Aside from the effect of changing proportions of SiO_2, the indices of refraction of the artificial glasses are determined by all the other major constituents of oxides. We have studied some published data on the optical properties of glass [*Morey*, 1938] in the hope of finding out in what order the indices of refraction of artificial glasses are determined by the oxides. We found them in descending order as follows: Fe_2O_3, TiO_2, FeO, MgO, CaO, Na_2O, and K_2O. The magnitude of effect of these oxides on the index of refraction glass is shown in Table 1. This order holds true in glasses of binary or ternary systems. Yet, we could not state blankly without adequate data that this order also holds true in glasses of multi-component systems such as artificial glasses made of rock samples. In other words, this order may vary in glasses of multi-component systems. Also this

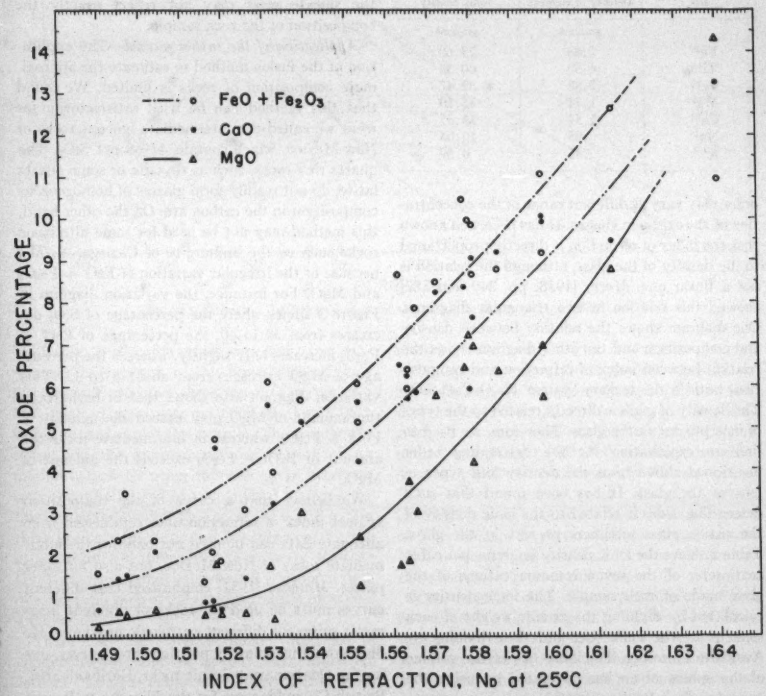

FIG. 2 – Curve shows the relation between index of refraction and the percentages of MgO, CaO, and the combined Fe_2O_3 + FeO, based on analyzed samples of some volcanic rocks of New Mexico

TABLE 1 — *Effect of various oxides on the index of refraction of glasses of binary or ternary system with silica*

Oxides in glasses of binary or ternary system with SiO_2	Increase of index of refraction of the glasses per one percent increase of the oxide (approximate)[a]
Fe_2O_3	0.0068
TiO_2	0.0063
FeO	0.0061
MgO	0.0044
CaO	0.0030
Na_2O	0.0013
K_2O	0.0011

[a] The relation between the composition and index of refraction is not a linear one.

TABLE 2 — *The ionic density of the cations which occur as modifiers in silicate glass*

Ion	Density of element	Ionic density
	gm/cm^3	gm/cm^3
Fe^{2+}	7.88	73.60
Ti^{4+}	4.50	60.38
Fe^{3+}	7.88	52.47
Mg^{2+}	1.74	35.10
Ca^{2+}	1.54	16.37
Na^{1+}	.95	10.63
K^{1+}	.85	6.59

order may vary at different range of the concentration of the oxides in glasses. It has been well known that the index of refraction is directly proportional to the density of the glass, although the relation is not a linear one. *Morey* [1938, pp. 249 and 387] showed this relation in two triangular diagrams. One diagram shows the relation between density and composition and the other diagram shows the relation between index of refraction and composition, both in the ternary system Na_2O-CaO-SiO_2. The density of glass is directly related to the types of ions present in the glass. Therefore, we tried to find an explanation for the descending order mentioned above from the density and types of ions of the glass. It has been found that such descending order is related to the ionic density of the cation glass modifiers present in the glass. Table 2 shows the ionic density in grams per cubic centimeter of the seven common cations of the glass made of rock sample. The ionic density is calculated by dividing the atomic weight of each element by the ionic size, and then dividing by Avogadro's number. The ionic size is the volume of the sphere of an ion calculated by using the crystal radii of *Pauling* [1945].

(4) Because of the presence of oxygen and carbon atoms and molecules in the carbon-arc column, some the ferrous ions of the powdered rock sample may be oxidized into ferric ions, or some of the ferric ions may be reduced into ferrous ions. It has been observed that brown colored glass bead was formed of light gray powdered rock sample in the carbon arc. Evidently some ferrous ions of the rock sample have been oxidized into ferric oxide. There is no way to control the reduction or oxidation of these ions in the arcing. Therefore, the index of refraction of the silicate glass may vary because of the change of the valence of the ions.

The silicate glass bead formed in the carbon arc may have slightly different composition as compared with the powdered rock sample, because portion of silicon and the alkali metals of the rock sample may have distilled after the arcing. The alumina content of the silicate glass may be enriched relatively. Thus, the index of refraction of the silicate glass may not reflect exactly the composition of the rock sample.

Application of the fusion method—The application of the fusion method to estimate the approximate composition of rocks is limited. We found that this method can be used satisfactorily for what we called the intermediate igneous rocks of New Mexico, which contain 44–68 pct SiO_2. The quartz-rich rocks, such as rhyolite or some quartz latite, do not readily form glasses of homogeneous composition in the carbon arc. On the other hand, this method may not be used for some ultrabasic rocks such as the limburgite of Cienega, N. M., because of the irregular variation of FeO + Fe_2O_3 and MgO. For instance, the variation diagram in Figure 3 shows where the percentage of SiO_2 decreases from 50 to 40, the percentage of FeO + Fe_2O_3 increases only slightly, whereas the percentage of MgO increases from about 6 to 12. This variation diagram also shows that in basic rocks the amount of MgO may exceed the amount of FeO + Fe_2O_3, whereas in intermediate rocks the amount of FeO + Fe_2O_3 exceeds the amount of MgO.

We believe that a curve of the composition against index of refraction once established from adequate data can be used not only for the intermediate rocks of New Mexico, but also for other places. *Mathews* [1951] emphasized that different curves must be used for rocks of different magmatic suites, or different petrologic provinces. He illustrated this point by plotting three curves, one for the Quaternary volcanic rocks, Garibaldi area, British Columbia; one for the Pliocene to Recent volcanic rocks, Mt. Lassen, California; and one for the late Tertiary volcanic rocks, Markleeville area,

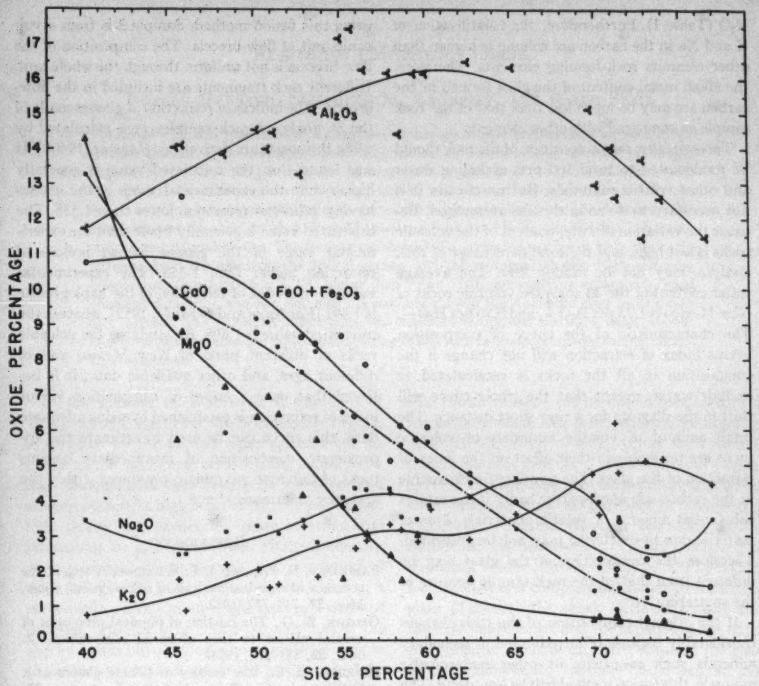

FIG. 3 – Variation diagram of some of the volcanic rocks of New Mexico

California. But for practical purposes, and considering the accuracy of this fusion method, it is not necessary to have three separate curves. We have plotted one curve by using Mathew's data which he used to plot three curves. The accuracy in estimating the approximate composition of an unknown rock by using this one curve decreases only about half per cent as compared by using the three separate curves. This accuracy is still within three per cent for silica and two per cent for the other oxides. The three separate curves of *Mathews* [1951] may not remain the same if additional data of rocks from each of the three petrologic provinces are available.

There may be some irregular variations of composition of suites of igneous rocks which are formed through magmatic differentiation from basaltic magma in different petrologic provinces. However, no matter where these igneous rocks occur, or what their ages are, these rocks as a whole show a gradual variation of their oxides content with respect to silica. Such gradual variation is illustrated by the variation diagram of some volcanic rocks of New Mexico in Figure 3. This diagram shows that with the increase of silica, the percentages of MgO, CaO, FeO and Fe_2O_3 decrease. Also both K_2O and Na_2O increase. The amount of Fe_2O_3 + FeO is usually greater than CaO, which in turn is greater than MgO. In the volcanic rocks of New Mexico we have studied, the amount of Na_2O is usually greater than K_2O, except where the silica content is greater than 68 pct.

Intermediate rocks of one petrologic province may contain a higher amount of K_2O or Na_2O than that of another petrologic province. A few per cent variation of the K_2O or Na_2O may not be detected by the fusion method, because one per cent increase of K_2O in the glass will affect the index of refraction of the glass by only about 0.001. Na_2O has a slightly higher effect on the index of refraction than

K_2O (Table 1). Furthermore, the volatilization of K and Na in the carbon arc column is higher than other common rock-forming elements. Therefore, the alkali metal content of the glass formed in the carbon arc may be much less than that of the rock sample as compared with other elements.

Theoretically, the composition of the rock should be recalculated to total 100 pct, excluding water and other volatile materials. But practically it is not necessary to do so in this fusion method. Because the variation of water content of the volcanic rocks is not high, and the total percentage of rock analysis may not be exactly 100. The average water content of the 36 analyzed volcanic rocks of New Mexico is 1.73 pct H_2O+, and 0.50 pct H_2O-. The characteristic of the curve of composition versus index of refraction will not change if the composition of all the rocks is recalculated to exclude water, except that the whole curve will shift in the diagram for a very short distance. The small amount of volatile materials of volcanic rocks are negligible in their effect on the index of refraction of the glass. The powdered rock sample in the carbon arc may spatter badly if it contains substantial amount of volatile materials. Loss of material due to spattering may not be prevented. Therefore the composition of the glass may be different from that of the rock sample because of the spattering.

If the original composition of the rock changes considerably because of introduction of secondary minerals such as calcite or other metasomatic minerals, this fusion method will be less useful. The fusion method is not good for estimating the approximate composition of metamorphic rocks with reasonable accuracy, based on the results of the study of ten metamorphic rocks for which complete chemical analyses have been obtained. Whenever there is a considerable amount of calcite in the rock sample, it is better to recalculate the composition of the rock by eliminating the carbon dioxide. If so, most of the plotted points of carbonate-rich rock samples, such as 1, 2, and 5, in Figure 1 will be close to the curve. Open circles 1A, 2A, and 5A are corresponding points which represent the composition of the rock samples including the carbon dioxide.

Result and conclusion—It has been found to be satisfactory to correlate and to estimate the approximate composition of about 200 rock samples by using the curve of composition versus index of refraction shown in Figure 1. However, there are a few rocks, such as represented by Sample 3 in Figure 1, that have been difficult to correlate by using this fusion method. Sample 3 is from a volcanic unit of flow-breccia. The composition of the flow-breccia is not uniform through the whole unit. Different rock fragments are included in the flow-breccia. The indices of refraction of glasses made of the 36 analyzed rock samples were calculated by using the constants derived by *Huggins* [1940b]. It was found that the calculated value is generally higher than the experimental value of the glasses having indices of refraction lower than 1.538. The calculated value is generally lower than the experimental value of the glasses having indices of refraction higher than 1.538. The experimental value of the index of refraction of the haplogranite is 1.491 [*Fairbairn* and *Schairer*, 1952], whereas the calculated value is 1.498. By studying the volcanic rocks of different parts of New Mexico and of different ages, and other available data, it is believed that once a curve of composition versus index of refraction is established by using adequate data, this curve can be used to estimate the approximate composition of intermediate igneous rocks of different petrologic provinces within the accuracy mentioned above.

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Australite (Meteoric) Glass

DONALD HUBBARD, ELIZABETH M. KRUMRINE, AND RALPH STAIR

Abstract—Typical specimens of Australite (tektite) glass have been studied for such properties as expansivity, annealing temperature, chemical durability over an extended pH range, hygroscopicity, electrode pH response, heterogeneous equilibria at the liquid-solid interface, and spectral transmittance to ultraviolet, visible, and infrared radiations. The results obtained on this glass, supposedly of extra-terrestrial origin, have been compared with similar data obtained on obsidian glass from Yellowstone Park, and some present-day industrial, optical, and natural glasses. The comparison showed the Australite specimens to be distinctly different from the obsidian, the optical glasses, and the industrial glasses. High softening temperature (approximately 175°C higher than Pyrex 7740), intermediate expansivity, good chemical durability, and low electrode pH response showed the Australite glass to be generally superior. The spectral transmittance was inhibited throughout the ultra violet, visible, and infrared regions by the presence of coloring oxides such as iron, chromium, copper, nickel, and manganese.

In the summer of 1952 when a squadron of 'flying saucers' sped over the Washington airport, as revealed by the ground radar systems but invisible to the naked eye, besides being inaudible, it was obvious that the 'Flying Saucer Era' had already attained a high order of cultural perfection; that reality had something more startling and interesting to offer even than Flash Gordon or science fiction. Technological and psychological skills being what they are in the 20th century, a person with a fertile mind might have extrapolated progress into the future and concluded that the sky by now is full of flying saucers invisible even to the radar screen. However, as the true nature of the many types of flying saucers is becoming better understood [*Menzel*, 1953] and less apprehension is felt as to their sinister character, one can follow without hysteria the hypothetical fate of one type of flying saucer, namely a mass of interplanetary jetsam composed of glass as it arrives at the outer edge of the atmosphere and comes in for a landing upon the Earth's surface.

Such a 'saucer' upon entering the Earth's gravitational field would be at some frigid equilibrium temperature, certainly not lower than −223°C [*Ewen*, 1952], as a result of absorption of solar and other cosmic radiant energy, and reradiation back into space. It would enter the upper atmosphere at a speed ranging from about seven to near 45 mi/sec, depending on whether the meteor was overtaking the Earth or was being met head on [*Chapman*, 1952]. Higher speeds are possible only if the meteorite comes from outside the solar system along a hyperbolic path, but radar observations indicate that the great majority of meteors do not arrive at hyperbolic speeds. At such speeds friction with the air causes a sudden rise in temperature of the surface which has been reported at times to equal 2200°C [*Federer*, 1952]. Under such circumstances metallic meteors of relatively small size are melted, ablated, and partially oxidized, whereas stony meteors may be partially or completely volatilized or ablated. However, one made of glass cannot oxidize because it is already composed of elemental oxides [*Barnes*, 1940, p. 530]. Further, for a meteor of a composition similar to Australite glass (Table 1) the shock initiated by the low internal temperature and the expanding hot outer surface must result in excessive strain in the glass object which would continue to be exerted and increased over the temperature interval from −223°C to about 650°C, which latter temperature is in the 'critical' region commonly known as the annealing range of the glass (Fig. 1). Thus the glass is vulnerable to breakage over a temperature range of approximately 873°C before any effective release of stress can be attained. To release such stresses, the surface of any body must increase. Glass has little or no capacity for surface alteration below the critical and softening temperatures except to break or form cracks at the points where the forces exceed the tensile strength of the glass. Common silicate glasses are particularly vulnerable because stresses exerted upon a brittle material, instead of being uniformly distributed throughout the mass, are preferentially concentrated at surface defects.

A qualitative review of the thermal endurance of glass [*Tooley*, 1953] will give a fairly acceptable picture of the fate of any glassy meteor speeding into the Earth's atmosphere. The thermal shock that a glass can withstand is dependent on the

TABLE 1. – *Composition of glasses arranged in the order of decreasing percentage of SiO_2*

Oxide	Fused SiO_2	Libyan Desert glass[b]	Opal	Vycor	200-inch reflector Mt. Palomar Telescope	Pyrex 7740	Kimble N51-A	Obsidian, Yellowstone	Corning 015 electrode glass	Australite (meteoric)[b]	BSC 517	Soda flint	Fiber glass	BaC 572	F 620
	pct	pct	pct	pct		pct	pct	pct	pct	pct	pct	pct	pct	pct	pct
SiO_2	99.6	97.58	98–87	96.3		80.5	74.7	74.7	72.0	70.6	66.4	60	55	49.7	45.6
TiO_2	...	0.21	...	...		...	...	...	...	0.9	...	...	...	...	...
B_2O_3	...	...	...	2.9		12.9	9.6	...	...	...	12.4	...	9.5	3.6	...
As_2O_3	...	...	...	0.005		...	0.03	...	...	...	0.5	...	...	0.2	0.5
Sb_2O_3	...	...	...	...		...	...	...	...	...	...	...	...	0.4	...
Al_2O_3	...	1.54	...	...	Special borosilicate	2.2	5.6	13.72	...	13.5	...	...	14.5	...	...
Fe_2O_3	...	0.11	...	...		...	...	1.01	...	0.85	...	...	...	...	...
FeO	...	0.23	...	0.4		...	...	0.62	...	4.44	...	...	...	...	...
MgO	...	...	...	...		...	...	0.14	...	2.4	...	...	5.0	...	...
CaO	...	0.38	...	...		...	0.9	0.78	6.0	3.1	...	...	16.0	...	...
BaO	...	...	...	...		...	2.2	...	...	...	...	...	...	30.8	...
ZnO	...	...	...	...		...	0.1	...	...	...	0.5	...	...	7.2	...
PbO	...	...	...	...		...	...	...	...	...	...	20	...	...	45.1
MnO	...	...	...	...		...	...	...	...	0.42	...	...	...	...	...
H_2O	...	0.10	2–13	...		...	...	0.62	...	0.07	...	...	...	...	...
Na_2O	...	0.34	...	0.2		3.8	6.4	3.9	22.0	1.3	8.4	20	...	0.4	3.6
K_2O	...	...	...	0.2		0.4	...	4.02	...	2.2	11.8	...	...	7.7	5.2
	[a]	...	...	...		...	...	...	...	...	[a]	[a]	[a]	[a]	[a]

[a] Calculated from batch composition.
[b] From *Barnes* [1940, p. 530].

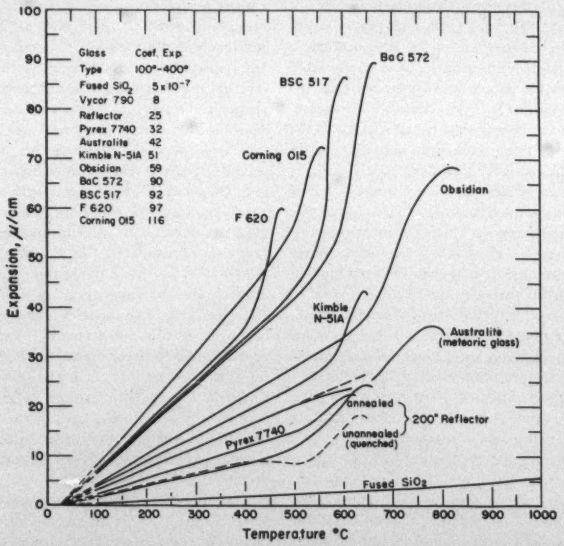

FIG. 1 – Expansion characteristics, annealing and softening temperature ranges of Australite (meteoric) glass, some modern industrial, typical optical and special purpose glasses; data obtained by Herman F. Shermer and L. H. Maxwell

properties appearing in the equation: $\Delta T = (nP/\alpha E)\sqrt{K/sc}$ where ΔT is the temperature gradient that can be withstood; P, the tensile strength of the glass; α, the coefficient of thermal expansion; E, Young's modulus; K, thermal conductivity; s, density; c, specific heat; n, a proportionality constant. Of these properties the coefficient of expansion varies considerably with changes in composition (Fig. 1 and Table 1), while the ratio K/sc does not change so markedly. A simpler equation $\Delta T = n'P/\alpha\sqrt{L}$ may be substituted, where n' is a constant, L is thickness, while P and α represent the same properties as before. This equation emphasizes the fact that the thermal shock which can be endured is inversely proportional to the coefficient of expansion and the square root of the thickness. As the thermal conductivity of glass is entirely inadequate to equalize rapidly the temperature throughout its mass, a disruption of the interplanetary glass visitor is inevitable. A superficial idea as to the limited shock that can be withstood is furnished by tests on Erlenmeyer flasks of laboratory glass ware. Two Pyrex series gave a preponderance of breaks for temperature gradients between 250° and 300°C, and a similar series of Kimble flasks gave maxima at 175° and 250°C. [*Wichers* and others, 1941]. Pyrex 7740 and Kimble N-51A were chosen for comparison because the coefficient of expansion for the meteoritic glass falls between the expansion coefficients of these two superior laboratory glass wares (Fig. 1).

Glassy meteorites of higher coefficient of expansion, comparable to that of the optical glasses (Fig. 1), would be even more severely shattered. Those of low viscosity or low working temperature would be more completely ablated into tails, aprons, thin sheets, or threads. Such glasses might not even reach the ground in recognizable form. If they happened to be of poor chemical durability or high hygroscopicity or both, any bits that did arrive would be of short life on a geologic scale. (Sterling B. Hendricks has suggested that only glasses of low coefficient of expansion and superior chemical durability might survive, and thus a large percentage of tektites discovered would be expected to be of a 'super Pyrex' nature, namely, low expansivity, superior chemical durability, low hygroscopicity, a weak tendency toward devitrification, and a very high working temperature.)

Thus, it is obvious that a glassy meteorite would be shattered as it sped earthward, and the fragments widely scattered along the direction of flight. (The experiment of plunging white hot pieces of the glass into water [*Barnes*, 1940, p. 554] to show that thermal shock would not shatter a glassy meteor of the tektite composition upon striking the Earth's atmosphere is a most unfortunate choice. Quenching involves the compressive strength of glass, and is used commercially to produce glass articles of great strength and shock resistance, such as 'case hardened' glass plates, tempered articles, and even glass springs for operations where metals are unacceptable because of the latter's fatigue and magnetic characteristics. This same feature plays a critical and spectacular role in cooling pots of molten optical glass. Solids may be obtained which can be broken open with difficulty, resulting in destructive 'cathedral Spires,' or in 'vacuum bubbles' and 'onions.') The smaller fragments would lose speed rapidly and fall behind. The retarding force of the air varies as the second power of the velocity of the falling body. When the retarding force becomes just equal to the weight, a body moves downward with a constant 'limiting speed.' This speed at which the resistance offered by the air equals the weight of the body is determined by factors appearing in the equation: $(c\rho v^2/2)\ A = W$, where c is the drag coefficient or shape factor which varies from approximately 0.3 for a polished sphere to 0.5 for a rough sphere to 1.0 for irregular shapes; ρ, the density of air, which under standard conditions (760 mm pressure and 15°C) has the value of 0.002378 slugs per cu ft where slugs is lb/32.2; v, the velocity in ft/sec; A, the projected area in feet^2; and W, the weight in pounds.

Thus the limiting speed for a sphere one inch in diameter of the density 2.3 for glass would be near 80 mi/hr. This value would vary with the shape of the particle and condition of its surface, but it serves to illustrate that the shattered fragments of an extraterrestrial glassy missile could flutter in for a landing on the Earth's surface at speeds as low as 100 ft/sec.

Concerning the temperature of these fractured specimens during the latter stages of their flight, temperatures up to 2200°C have been observed for other types of meteors, but the tektite glass is vulnerable to breakage through a temperature range of almost 900°C before it can effectively withstand severe thermal shock. During this temperature rise it would break up into smaller units until the fragments attain such size that they can withstand the thermal shock initiated by a continued large negative acceleration and cold interiors.

From the appearances of all tektite specimens available, their surfaces had most certainly been plastic at some period prior to the moment of striking the ground, but were in some cases subject to fracture under the sudden sharp impact of their

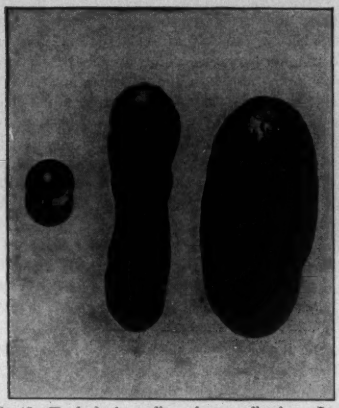

FIG. 2 – Typical Australites from collection, South Australian Museum, Adelaide; dumb-bell specimen 3¼ inches long; photo by William A. Cassidy

arrival. Some of the specimens apparently were chipped upon landing, and radial shock patterns can be observed at fracture points somewhat similar to those caused by a hammer blow, so familiar to the trimmers of raw optical glass. The surfaces of these chipped areas appear to be of the same age as the unfractured surfaces of the specimens. Specimen shapes range from near spheres, buttons, pancakes, dumb-bells, to crullers (Fig. 2), with or without thin aprons or tails streaming behind the leading face. Such specimens having these characteristic regular shapes certainly were not at the working temperature of the glass throughout their mass at the moment of landing, otherwise they would have been mutilated, flattened, or twisted. The specimens showing pronounced ablation from the leading surface must have attained temperatures on this face of at least 1500°C and possibly higher for a short period of time during their flight, because a glass of the characteristics found for Australites (Fig. 1) would not be sufficiently fluid at lower temperatures.

That the fragments could possibly be in such good condition or have even survived the trip at all seems almost incredible in view of the amounts of energy that had to be dissipated in arresting their flight. Figure 3 shows the kinetic energies in calories for a one-gram particle traveling at speeds ranging from 0 to 60 mi/sec. Thus the heat available from one-gram matter having a velocity of 50 mi/sec is approximately 800,000 calories.

That the particles had successfully dissipated

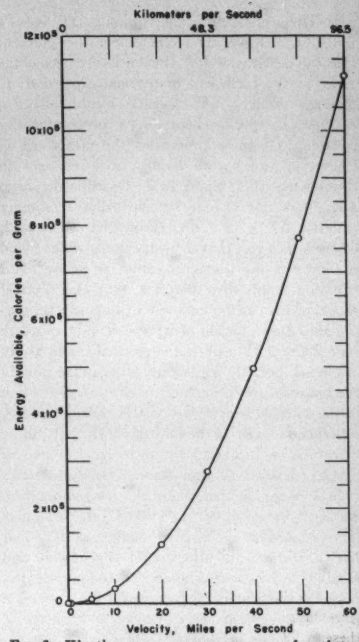

FIG. 3 – Kinetic energy per gram as a function of speed; some extraterrestrial visitors are known to arrive with speeds exceeding 40 mi/sec

this enormous energy by such mechanisms as compression of the air mass in front, rarefaction behind, resistance to air displacement, vibration, heat of fusion, ionization, reradiation, conduction, and convection; and that their pace had been reduced in turn from the hypersonic realm to supersonic, transonic, and subsonic speeds, to near the terminal velocities is evident from the fact that they did not explode nor were they even severely shattered upon impact. Experiments reported by the United States Army Ordnance Department have shown that inert missiles will explode on striking a solid at 4 to 5 mi/sec [*Nininger*, 1952]. Thus it is obvious that going from hypersonic to subsonic speeds, breaking the sound barrier in reverse, presents grave problems and hazards. The major defense of the tektite glasses against complete destruction appears to be their very high softening temperature, their small thermal conductivity coupled with the fact that the interiors were initially cold.

In support of the validity of this general picture of such flights by glass meteors, a myriad of irregular and rounded shaped, small glass fragments (Fig. 2) that qualitatively fulfill all of these expectations are found scattered over vast areas in Australia and elsewhere [*Barnes*, 1940, p. 486; *Nininger*, 1952] where they possess no chemical or geological features compatible with their present environment.

In light of the mystery surrounding the origin of tektites, it is of more than passing interest to compare some of the properties of other more familiar industrial, optical, and natural glasses with typical samples of Australites, and to obtain if possible a better understanding of these latter as yet unique geologic misfits [*Nininger*, 1952]. The Australite specimens on which the following comparisons are made were furnished by William A. Cassidy in 1953 while he was Research Assistant, Institute of Meteoritics, and Fulbright Fellow for graduate study, University of Adelaide, Australia.

Expansion characteristics of Australites—Figure 1 shows the expansion curve for a characteristic specimen of Australite glass compared with other materials. This expansion curve shows that the specimen had been cooled from above the 'critical' temperature range sufficiently fast to prevent thorough annealing as indicated by the pronounced decrease in the rate of expansion between 550° and 650°C. This same feature is well illustrated by the expansion curves for the quenched and annealed sample of the special borosilicate glass used in the 200-inch Mt. Palomar reflector telescope. This slightly disannealed condition of the tektite glass as shown by the expansion curve is compatible with the cold-hot-cool flight pattern for the surface of these meteoric fragments while coming in for a landing, regardless of the state of annealing of the parent mass at the time it arrived at the tenuous outer edge of the Earth's atmosphere. If a section of Australite glass were found that was sufficiently large to insure that it had not been heated above the critical temperature (approximately 650°C) throughout its mass during the brief flight through the Earth's atmosphere, then it would be possible to know if the glass had been cooled slowly or quickly at its point of origin where the glass was initially produced. If it showed a normal expansion curve as is the case for the obsidian sample shown in Figure 1 this would indicate a slow rate of cooling. This in turn would mean that all of the impact-molten-splash and volcanic eruption theories offered for the origin of tektites would be untenable [*Barnes*, 1940; *Nininger*, 1952]. All of these mechanisms would involve severe quenching conditions which would unquestionably result in a much more distorted expansion curve than that shown for the Australite glass in Figure 1. One of the larger specimens cut and polished for spectral transmittance measurements showed little or no strain patterns except around the periphery when viewed in the polariscope. Although these conditions for observing the anisotropy of Australite glass were not favorable, because of the dark color and thin section, this observation does suggest that the Australite glass was not produced and cooled initially under catastropic circumstances.

Certainly the Australite glass was produced at temperatures that exceeded 1500°C, probably nearer 2000°C. Apparently a glass of the Australite composition could not be melted below 1550°C as shown by the phase equilibrium diagram for the K_2O-Al_2O_3-SiO_2 ternary system [*Schairer* and *Bowen*, 1947]. Then to 'fine' (that is, remove the dissolved gases) this glass compatible with the seed quality of the Australite glass specimens would require considerably higher temperatures. Further, the molten glass must have been maintained in the liquid state at this elevated temperature sufficiently long to allow the escape of reaction gases. During this period no sudden release of pressure occurred, otherwise some type of foam glass would have resulted. It then necessarily cooled sufficiently slowly to prevent the formation of 'vacuum bubbles' which are produced when large masses of glass are cooled through the 'critical range' too rapidly. Such bubbles vary in size from a few millimeters to as large as a person's head. Epidemics of this spectacular and destructive 'disease' have often harassed optical glass plants using the pot-transfer procedure [*Wright*, 1921].

The Australite glass apparently was melted on a celestial body that had an ample supply of oxygen at the time the batch materials were produced or during the melting period because all of the elements found in the glass including the hydrogen are present in an oxidized state (Table 1).

Inspection of the striae patterns (Fig. 4) of tektite specimens shows that the glasses were not stirred adequately during the fining and cooling periods to give them optical homogeneity [*Barnes*, 1940, p. 582]. Equally interesting is the fact that the striae are not oriented at the surface, but are essentially random as might be expected if the specimens had been broken from a larger mass. Further, index of refraction determinations with the petrographic microscope made independently

FIG. 4 – Striae pattern of a thin cross section of a tektite (0.5 mm thick) as shown by transmitted light

by G. F. Rynders and Given W. Cleek revealed that the Australite glass is far from homogeneous, varying in index from 1.504 to as high as 1.524 over a small cross section. Furthermore, in polarized light localized points were found to be birefringent indicating incipient crystallization. Anisotropy due to poor annealing would not appear in these small crushed samples.

The low expansion characteristics and high deforming temperature approximately 175°C higher than Pyrex 7740 fit well into the tentative requirements as proposed by Hendricks, noted above. Glasses having characteristics shown by the BaC 572, BSC 517, Corning 015 and F 620 would be expected to shatter into smaller bits, ribbon out into thin sheets and threads more rapidly. Furthermore, such thin sections of the optical types (BaC 572, BSC 517, F 620, and the soda flint) would be of relatively short life because of their very inferior

FIG. 5 – Typical interference pattern for a specimen of glass after the lower portion was exposed at pH 4.1, indicating a surface alteration-swelling of approximately $\frac{1}{2}$ fringe ($\frac{1}{4}$ wave length of the 5876 Å spectral line of helium; this is equivalent to approximately 3×10^{-6} inches)

chemical durability as illustrated by Fig. 5, and shown in Figure 6b.

The expansion curve for fused SiO_2 is included in Figure 1, because some types of meteoric glass (Libyan Desert glass) are approximately 98 pct silicon dioxide. Obviously the smaller the coefficient of expansion the greater the thermal shock that can be endured without breaking, hence the larger the average particle size arriving at the Earth's surface. For example, if a meteoric glass had a coefficient of expansion equal to zero, the temperature gradient $\Delta T \propto 1/\alpha$ that it could endure would be infinite, that is, no breakage from thermal shock would occur. In accord with this reasoning, transparent and translucent Libyan tektites that are largely fused silica are found in pieces as large as 10 and 16 lb [*Barnes*, 1940; *Nininger*, 1952].

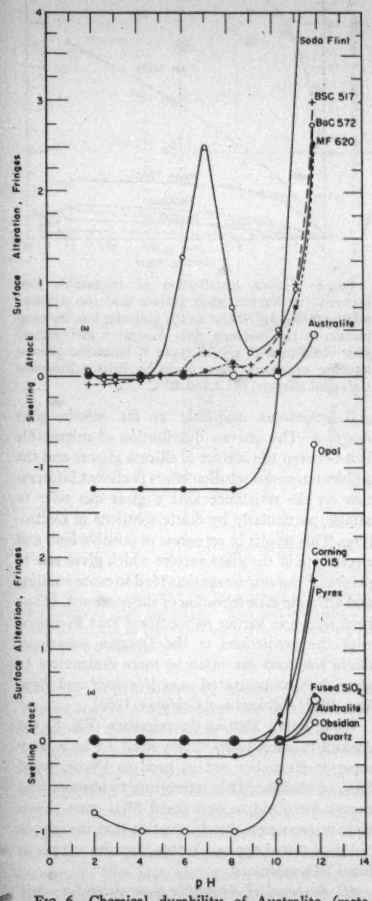

FIG. 6 – Chemical durability of Australite (meteoric) glass compared with (a) obsidian, two commercial glasses, and three forms of silica (quartz, fused silica, and opal); (b) three typical optical glasses (borosilicate crown, BSC 517; light barium crown, BaC 572; and medium flint, F 620 and an experimental soda-lead oxide-silica flint (soda flint); data on optical glasses obtained by B. R. Nebel

Chemical durability of Australite glass—The chemical durability measurements were made using an interferometer procedure which indicates surface alterations, in wave lengths of light, of polished flats upon exposure to various solutions under controlled conditions of time temperature, and pH (Fig. 5). (These flats were prepared by Earl F. Webb of NBS optical shop who pointed out the ease with which this Australite Glass lent itself to sawing, grinding, and polishing, and also remarked at the brilliance and attractiveness of the finished surfaces.)

In Figure 6a one sees that the chemical durability of the Australite glass compares favorably with that of fused SiO_2, is far superior to that of opal, but not equal to that possessed by quartz. Corning 015 (the composition of which was chosen from phase equilibria data by George W. Morey because it is that of the lowest melting eutectic of the Na_2O-CaO-SiO_2 system; the same composition was chosen independently by D. A. MacInnes and Malcolm Dole because of its superior electrical response to hydrogen ion activity of aqueous solutions) opal, and the soda—flint glass (Figure 6) are examples of glassy and natural silicates that exhibit swelling in acid solutions. The optical glasses included in Figure 6b are types which would not be expected to survive, geologically speaking, even if they should arrive successfully at the Earth's surface as meteoritic glass. (It is interesting to note Nebel's data in Figure 6 emphasize that little or no work has been reported in many years on improvement of the chemical durability of these optical glasses, even though their poor chemical durability has been contributory to the excessive deterioration of optical instruments and spectacle lenses Conspicuous examples are furnished by the severe etching of the glass brought about by the mycelia of fungus growths upon the polished surfaces of optical elements. [*Hutchinson*, 1946].) On the other hand the Australite glass and the Libyan Desert tektites

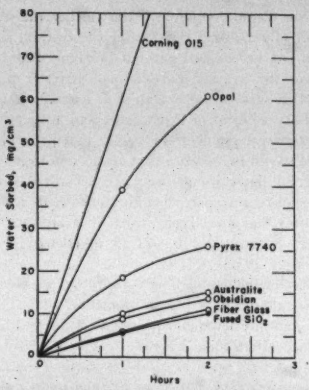

FIG. 7 – Hygroscopicity (water sorbed) of Australite glass compared with obsidian, superior commercial glasses (fused SiO_2, Pyrex 7740), fiber glass, and Corning 015 electrode glass

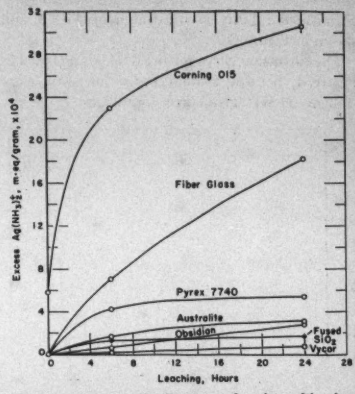

FIG. 8 – Uneven distribution of migratable ions between the leached glass surface and the ambient solution using $Ag(NH_3)_2^+$ as the indicator ion, for comparison of the meteoric glass Australite and natural glass obsidian with special types of industrial glasses; leaching exposures were made to Britton-Robinson Universal mixture, pH 4.1 at 80°C

(fused silica) would stand a maximum chance of survival based on their respective superior chemical durabilities. The latter especially would long endure because the average mass of the individual fragments at the time of arrival should be considerably larger for the Libyan tektite type than for the Australite based on their respective coefficients of expansion (Fig. 1).

Hygroscopicity of Australite glass—Another property that contributes to the survival ability, at least to the maintenance of clear polished surfaces, is the hygroscopicity, or capacity to absorb water vapor. The optical glasses whose chemical durabilities were observed to be so inferior in Figure 6b fortunately are very nonhygroscopic, hence are well able to maintain the fidelity of their polished surfaces for optical elements under normal atmospheric exposures. Figure 7 presents a comparison of the hygroscopicity of Australite glass with a few glasses of interesting properties. Pyrex 7740, a superior glass of low hygroscopicity when compared with a large number of commercial glasses of the window and container types, serves as a satisfactory reference. The curve for the Australite glass falls considerably below that of Pyrex 7740, but above those for fused SiO_2, a fiber glass, and obsidian. The fiber glass was included in the comparison because it is a glass whose composition is essentially alkali free, whose low hygroscopicity makes it capable of maintaining a surface of high electrical resistance under exposure conditions of high relative humidity.

Heterogeneous equilibria at the solution-glass interface—The uneven distribution of migratable ions between the surface of silicate glasses and the ambient aqueous solution offers pertinent information on the resistance that a glass can offer to attack, particularly by dilute solutions of electrolytes. This results in an excess of positive ions and electrolyte in the glass surface which gives rise to persistent osmotic forces that tend to cause swelling and ultimate disintegration of the specimen. It has been shown in earlier publications that in accord with the predictions of the Donnan equations, dilute solutions can often be more destructive to glass than concentrated ones [*Hubbard* and *Rynders*, 1947; *Hubbard* and *Goldman*, 1952].

Using Pyrex 7740 as the reference (Fig. 8) the Australite once again shows itself to be a very superior glass, but not as good as Vycor, fused SiO_2, or obsidian. It is interesting to observe that curves for obsidian and fused SiO_2 cross. Even more interesting is the observation that the sample of Vycor tested appears better than the sample of fused SiO_2 examined.

pH Response of Australite glass electrodes—Any glass upon immersion in an aqueous solution develops an electromotive force at the liquid-solid interface. This voltage for some glasses serves as a reliable indicator of the hydrogen-ion activity of the solution and varies in quantitative accord with the predictions of the Nernst equation, $\Delta E =$

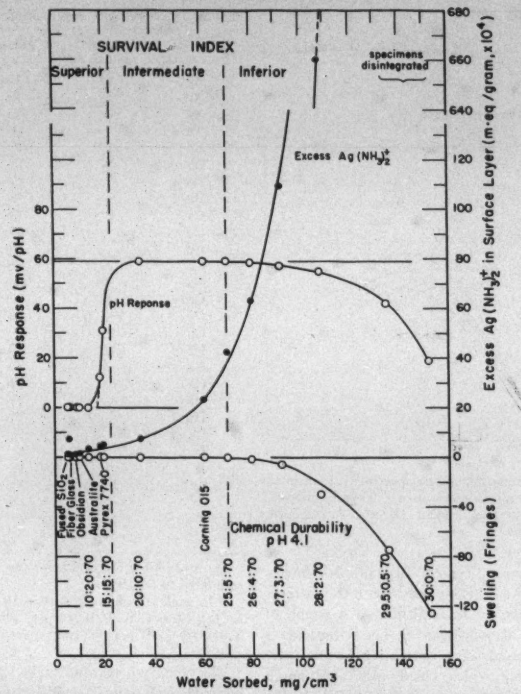

FIG. 9 – Comparison of the variation in pH response, chemical durability at pH 4.1, and the uneven distribution of migratable ions, $Ag(NH_3)_2^+$, with the hygroscopicity to furnish an overall picture of the position occupied by Australite glass as compared with other interesting glasses; a series of Na_2O-CaO-SiO_2 glasses having 70 pct SiO_2 are used as a reference

0.000198 $T\Delta$pH. However, glasses of very low hygroscopicity produce electrodes that fail to develope this theoretical 59 mv/pH at 25°C.

Figure 9 presents the pH response, chemical durability at pH 4.1, and the uneven distribution of migratable ions at the solution-glass interface for the Australite glass, plotted against the hygroscopicity. A series of soda-lime-silica (Na_2O-CaO-SiO_2) glasses having 70 pct SiO_2 are used as a reference. This plot also gives a comparison of any particular glass with other glasses for these four interesting serviceability or 'survival' characteristics. Glasses having a hygroscopicity greater than 70 mg/cm² are definitely inferior. They are characterized by high hygroscopicity, excessive swelling in acid solutions and buffers as shown by the chemical durability curve for pH 4.1; less than the theoretical pH response of 59 mv/pH at 25°C predicted by the Nernst equation; and adverse heterogeneous equilibria at the solution-glass interface. Silicate glasses falling in the hygroscopicity range designated as 'intermediate' are satisfactory for certain special purposes, notably the electrical response to hydrogen-ion activity of aqueous solutions, and 'cheap' container ware, but are definitely not satisfactory for many other uses. The Australite glass falls in the group labeled 'superior.' The hygroscopicity is low, the chemical durability is good, the heterogeneous equilibria is favorable and the pH response is negligible. The fiber glass seems to be acceptable in all properties except the uneven distribution of migratable ions after leaching at pH 4.1.

Spectral transmittance—In Figure 10 is shown

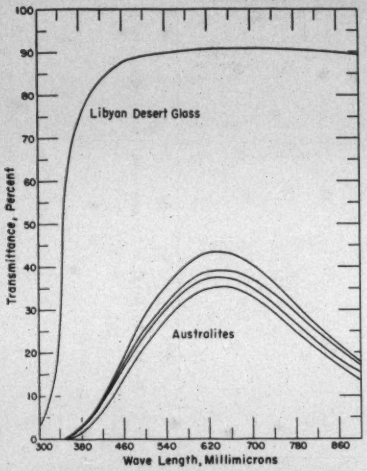

FIG. 10 – Comparison of the spectral transmittance from 300 to 900 millimicrons of two classes of meteoric glass, Australites and Libyan Desert glass; sample thickness 0.5 mm

the transmittance of typical Australite specimens. For comparison of the Australite with the extreme in meteoric glass, the transmittance of a sample of Libyan Desert glass is included. The latter glass is composed of fused silica containing a small percentage of other oxides, chiefly Al_2O_3. Although some of the Australite specimens studied had a better transmittance than others, all of those examined had a marked family resemblance. The strong absorption in the ultraviolet is primarily the result of the high iron oxide content. The transmittance throughout the visible is inhibited by the combined absorption from oxides of iron, nickel, chromium, manganese, and copper shown to be present by the spectrochemical analysis given in Table 2. This spectrochemical analysis of an Australite specimen gives ready information of the major constituents normally reported in chemical analyses, gives definite information on minor constituents often lost in the usual routine chemical procedures; but of far more importance it indicates the presence or absence of a majority of the elements of the periodic table. Therefore, as this technique can be refined to give quantitative data with but a few milligrams of sample, it should be one of the major tools in any serious study of the tektite problems.

TABLE 2 — *Spectrochemical analysis of Australite glass*

Element	Result[a]	Element	Result[a]
Ag	—?	Mo	—
Al	S	Na	M
As	—	Ni	T
Au	—	Os	—
B	VW	P	—
Ba	W	Pb	—
Be	—	Pd	—
Bi	—	Pt	—
Ca	S	Rb	—
Cb	—	Rh	—
Cd	—	Ru	—
Ce	—	Sb	—
Co	—	Sc	—
Cr	W	Si	VS
Cs	—	Sn	—
Cu	T	Sr	VW
Fe	M	Ta	—
Ga	—	Te	—
Ge	—	Th	—
Hf	—	Ti	M
Hg	—	Tl	—
In	—	U	—
Ir	—	V	VW
K	S	W	—
La	—	Y	—
Li	—	Zn	—
Mg	S	Zr	W
Mn	W		

Note: Limit of detection for the alkali elements is estimated to be 0.05 pct.

[a] In general: VS, greater than 10 pct; S, 1–10 pct; M, 0.1–1.0 pct; W, 0.01–0.1 pct; VW, 0.001–0.01 pct; T, 0.0001–0.001 pct; —, not detected.

The reduced transmittance in the red and infrared (minimum transmittance about 1200 millimicrons) is primarily the result of iron oxides. This shows up readily in Figure 11 in which the ultraviolet and visible ranges are compressed to a small portion at the left end of the curve, and the transmittance in the infrared extended to near 5000 millimicrons at which wave length the silicates have a sharp transmittance 'cut off.' One of the most conspicuous features of the infrared transmittance shown by characteristic tektite glasses from Australia and Bedias, Texas, is the absorption band between 2500 and 3000 millimicrons accredited to water. Although the curves for these widely separated specimens are quantitatively different they show a marked qualitative similarity.

In Figure 12 a specimen of Australite and one of Libyan Desert glass are compared with the glasses of commercial origin, Pyrex 7740, and fused silica. All of these glasses show the absorption band near 2800 millimicrons. The fused silica produced in an electric arc exhibits this band only slightly. The Libyan glass shows considerable individuality with

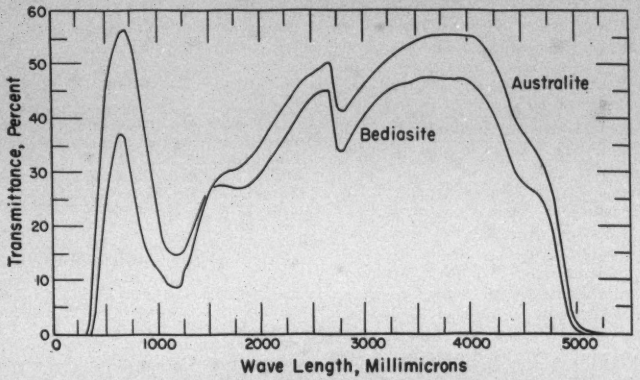

FIG. 11 – Comparison of the spectral transmittance from 300 to 5000 millimicrons of specimens of meteoric glasses from Australia and Bedias, Texas; sample thickness 0.5 mm

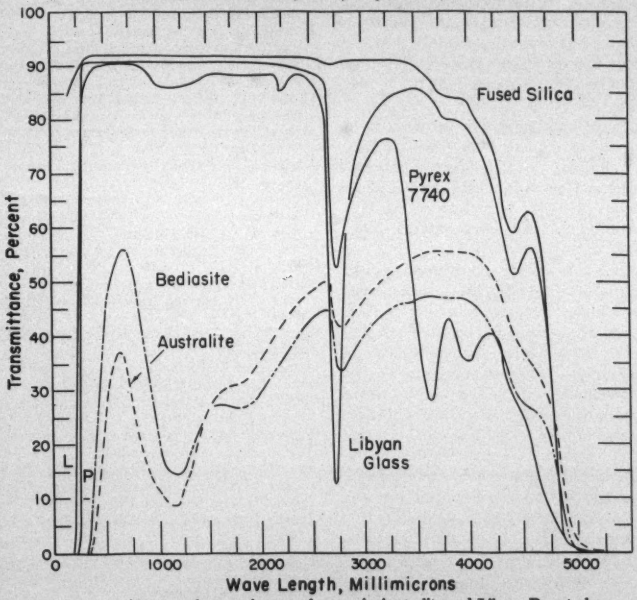

FIG. 12 – Comparison of the spectral transmittance of meteoric Australite and Libyan Desert glasses, with commercial fused SiO_2 and Pyrex 7740; sample thickness 0.5 mm

a very strong absorption here, another weak absorption near 2000 millimicrons, and a weak iron oxide absorption in the infrared around 1200 millimicrons. In the infrared region beyond 3500 millimicrons the Libyan glass and fused silica have absorption characteristics which are quite similar.

Concluding remarks—How far the investigators can go in solving satisfactorily the many intriguing

tektite problems remains to be seen. However, it is obvious that much interesting data leading to better and more complete understanding can be obtained from the continued use of the following tools:

(1) The spectroscope for the identification and evaluation of trace elements in glass [*Hubbard* and others, 1952].

(2) The mass spectrometer for a study of the isotopic abundance of elements present, particularly those retained as readily volatilized compounds [*Suess*, 1952].

(3) The interferometer and other dilatation procedures for determining the expansion curves and critical temperatures of the tektites from various showers for a comparison of the thermal shock characteristics with the average size of the specimens [*Hammond*, 1950].

(4) The spectrophotometer for obtaining special absorption characteristics over an extended range of wave lengths for the purpose of grouping and differentiating tektite showers from widely separated portions of the Earth's surface, as to their possible common origin in outer space [*Stair*, 1954; 1955; 1956].

(5) Equipment and procedures for the study of viscosity, surface tension, working temperature, liquidus, and other phase equilibria data of tektite compositions and appropriate experimental glasses in connection with the formation of the tails, aprons, streamers, shapes, and surface conditions observed for tektites.

Until recently Australites and tektites in general have had little practical relation to human activity except as curios, native good luck charms, an occasional rounded missile for the primitive sling shot, museum curiosities leading to conversational and mental gymnastics as to their age, manner, and place of formation; while the Australian bustard and emu have long made practical use of them as gizzard stones [*Fenner*, 1949]. However, in recent years as any definite communiques from extra-terrestrial sources have become more welcome the study of tektites has taken on, and will continue to take on a new interest. This is particularly true as space becomes more and more attractive as an exciting and intriguing frontier or even as a quiet retreat in case the present and future generations of practical jokers with their new atomic fire-crackers make the Earth too noisy for the satisfactory pursuit of the 'four freedoms.'

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Trigonometric Solution for Determining the Plunge of the Intersection of Two Dipping Planes

JOHN RODGERS

Abstract—The plunge of the intersection of two dipping planes can be determined by a simple formula parallel to Tanner's formula for determining true dip from two apparent dips.

Tanner [1956] has presented a simple trigonometric formula for determining true dip from two apparent dips. I was very interested in his formula because it was considerably simpler than a formula I had worked out for myself; I quickly verified that the two formulas are equivalent. As Tanner's is easier to use, I have discarded mine. But I had also worked out a precisely parallel formula for determining the plunge and direction of the intersection of two dipping planes and, starting from Tanner's paper, it was easy to derive a simple formula parallel to his for this problem also. I present it herewith, along with Tanner's formula for the apparent dip problem; I am using a different set of symbols from Tanner's, however, in order to demonstrate the parallelism of the two formulas and to bring out that the apparent-dip problem is only one way of phrasing the general problem of determining the plane containing two plunging lines.

The symbols are defined as follows:

δ = the true dip of a plane; it is measured in the vertical plane perpendicular to the strike of the dipping plane. Where there is more than one plane, $\delta_1 > \delta_2$, etc. Tanner likewise uses δ.

π = the true plunge of a line; it is measured in the vertical plane containing the line. Where there is more than one line, $\pi_1 > \pi_2$, etc. The line may be the intersection of two dipping planes, or it may be an apparent dip in a dipping plane, as measured in a vertical plane not perpendicular to the strike of the dipping plane. For apparent dips Tanner uses β and α. For the rake of a line, including an apparent dip, as contrasted with the plunge, I would use ρ, but it is not needed in these problems.

α = the angle between the strike of a dipping plane and the horizontal projection of a line (intersection or apparent dip) in that plane; it is measured in the horizontal plane. For this Tanner uses ϕ and θ.

β = the angle between the down-dip horizontal projections of the true dips of two planes or between the down-dip horizontal projections of the true plunges of two lines (or the directions of two apparent dips); it is measured in the horizontal plane. For this Tanner uses $x + y$; in the less usual case, not explicitly discussed by him, where the two apparent dips are taken in directions on the same side of the true dip direction, it would be $x - y$.

In determining the true dip of the plane containing two given lines, for example two apparent dips, one knows π_1, π_2, and β, and wishes to find α_1, α_2, and δ. Tanner's formula (in my symbols) is

$$\cot \alpha_1 = \frac{\cot \pi_1 - \cot \pi_2 \cos \beta}{\cot \pi_2 \sin \beta} \tag{1a}$$

which can also be restated

$$\cot \alpha_1 = \frac{\tan \pi_2 - \tan \pi_1 \cos \beta}{\tan \pi_1 \sin \beta} \tag{1b}$$

or, for easier calculation,

$$\cot \alpha_1 = \frac{\cot \pi_1 \tan \pi_2}{\sin \beta} - \cot \beta \tag{1c}$$

and

$$\cot \delta = \cot \pi_1 \sin \alpha_1 \tag{2}$$

In this case,

$$\alpha_1 > \alpha_2 \text{ and } \alpha_1 + \alpha_2 = 180° - \beta \tag{3}$$

Where the down-plunge directions of the two lines (apparent dips) lie on the same side of the true dip direction of the plane, α_1 is greater than 90°; it is obtuse.

In determining the true plunge of the line intersection of two dipping planes, one knows δ_1, δ_2, and β, and wishes to find α_1, α_2, and π. The parallel formulae are

$$\cot \alpha_1 = \frac{\tan \delta_1 + \tan \delta_2 \cos \beta}{\tan \delta_2 \sin \beta} \tag{4a}$$

or

$$\cot \alpha_1 = \frac{\cot \delta_2 + \cot \delta_1 \cos \beta}{\cot \delta_1 \sin \beta} \tag{4b}$$

or

$$\cot \alpha_1 = \frac{\tan \delta_1 \cot \delta_2}{\sin \beta} + \cot \beta \tag{4c}$$

and

$$\tan \pi = \tan \delta_1 \sin \alpha_1 \qquad (5)$$

In this case,

$$\alpha_1 < \alpha_2 \text{ and } \alpha_1 + \alpha_2 = \beta \qquad (6)$$

Where the down-dip directions of the two planes lie on the same side of the true plunge of the line (intersection), α_1 is less than 0°; it is taken as negative.

It is quite probable that others have already derived the formulae here presented for the intersection problem; if they have been published, I have missed them in the literature and must apologize for the duplication.

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Discussion

William F. Tanner (Department of Geology, Florida State University, Tallahassee, Florida)—The generalization suggested by Rodgers is a useful one. It is not clear, however, that the additional set of symbols achieves any purpose.

The vectors of apparent dips (that is, plunges), when plotted as tangents, give a sequence of points describing a circle which is tangent to the X-axis at the origin, and which has a diameter equal to the tangent of the true dip. From this figure one can develop either a graphic or a trigonometric solution. An example of the latter follows (symbols as in *Tanner* [1956]).

$$\tan y = \frac{\tan \alpha}{\tan \beta \sin (x + y)} - \cot (x + y) \qquad (1)$$

$$\tan \delta = \tan \alpha / \cos x = \tan \beta / \cos y \qquad (2)$$

It will be seen that this is quite similar to the formulas presented by Rodgers.

The solutions presented to date may be listed as follows: (1) vector analysis; (2) stereo net; (3) construction: laying off cotangents of apparent dip; values fall on straight line; (4) construction: laying off tangents of apparent dip; values fall on a circle; (5) trigonometry: three sets of formulas having minor differences.

Discussion of "Some Observations on Vertical Tectonics in Africa"

BY B. B. BROCK

[*Trans.*, **36**, 1044–1054, 1955]

V. L. Bosazza (39 Barkly Road, Parktown, Johannesburg, South Africa; received June 29, 1956)—Geologists in Africa and particularly those working south of the equator will agree with Brock that vertical tectonics play an important part in the structure of the Continent. Whether vertical tectonics are more important than orogeny in Africa as a whole is open to question as a great deal of Africa remains to be accurately mapped on the surface and of even greater importance is the elucidation of the structure in depth. In taking Africa as his subject, Brock is under a serious handicap in a relatively short paper, for condensing matter often means reducing the accuracy of certain descriptions, as the following examples show.

The Transvaal Dolomite and Karroo Basins—Of all the basins south of the equator these have been mapped accurately and, of even greater importance from mining and drilling data, the nature at depth has been determined even if the bottom of the basin has not been determined over great areas. Here I feel that Brock in dealing with African basins might have indicated that our knowledge of all these structures is not of equal rating, a point which I shall discuss with greater detail later. The conclusion that "the prevailing idea of a Transvaal Ocean extending over the greater part of the Continent is thus seriously questioned" followed by the view that it is not known how the dolomites or limestones were deposited in continental basins, is of course, purely a point of view and Brock has not given data proving his point of view.

First of all, to marine geologists, deposition in a sea and in an ocean, are two quite different matters. No geologist to my knowledge has postulated that the dolomitic limestones of the Transvaal System were ever deposited under oceanic conditions. In fact *Young* [1933, 1934] and *Young* and *Mendelssohn* [1948] have given very clear pictures of what they consider the conditions of deposition of dolomitic limestones. Young always considered that the limestones were deposited under conditions similar to those prevailing in the Bahamas today and those conditions are not oceanic.

Young started his word picture of the conditions of deposition as follows:

"There is abundant evidence that several of the Great Limestone formations of Palaeozoic and earlier age, including the Dolomite Series of South Africa, originated largely as calcareous muds and sands deposited in widespread shallow seas."

In detail he concluded:

"The area of deposits would appear to have been one of ever changing configuration, sometime permitting the undisturbed precipitation of fine calcareous muds, at other times exposed to intermittent tidal flooding sufficiently strong to transport calcareous sand and small mud-cake fragments, the accumulation of which by smothering growth in the depressions of the algal layers, brought about the characteristic branching."

Young [1933] had previously described what he meant by the terms 'shallow' and 'deeper.' At a later date Young and Mendelssohn [1948] described the remnants of plants and again the same environment was deduced. On Young's basis, I [Bosazza, 1937] had also come to the same conclusions regarding the conditions of deposition. Workers on the dolomite have, therefore, held the view that the conditions of deposition were most probably shallow marine, similar to the Bahamas area, and those conditions are not oceanic. Since then I have worked on the clays and shales interbedded in the Dolomite Series. These are typical saline water materials deposited in shallow water. Oceanic clays are quite different in character to these and thus the distinction is reasonably certain.

Many workers may consider that the difference between oceans and seas are purely matters of extent and depth but from an environmental point of view and the resulting products, a distinction must be made.

As regards the Karroo basin, in its characteristic development in the Karroo, it does not show structural control except in the south, and southwest. The western limits of the Karroo in the Western Cape Province, the northwest Cape Province and western Free State all show that the pre-Karroo surface is purely an erosional one. This can be quite clearly seen in the geological sections of Rogers and du Toit on the various sheet maps of the Cape Geological Commission (Fig. 4). The geology at depth is quite well known from the

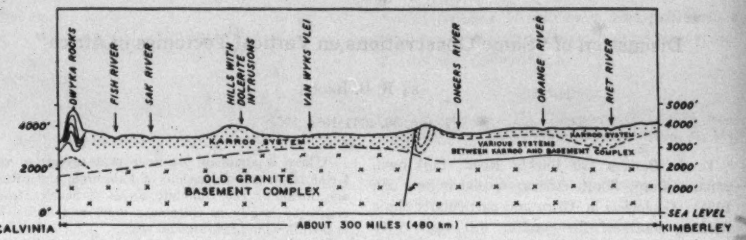

FIG. 4 – Geologic section showing Cape folded belt on the west and the erosional surface in which the Karroo sediments lie, bearing out that there is little or no structural control of the Karroo except in the Cape Folded Belt area

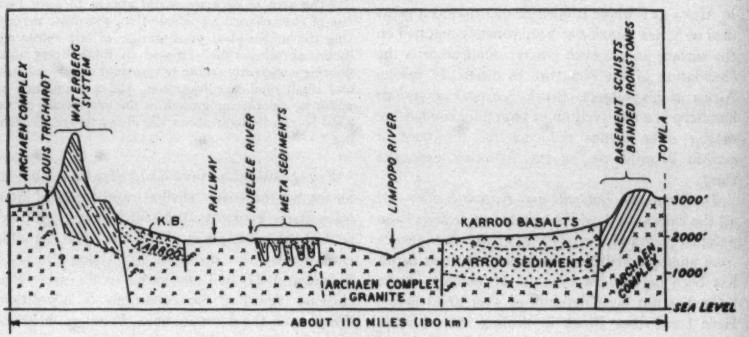

FIG. 5 – Section through Limpopo Trough; note the faults and the old folded structure and the subsidence of the Waterberg beds

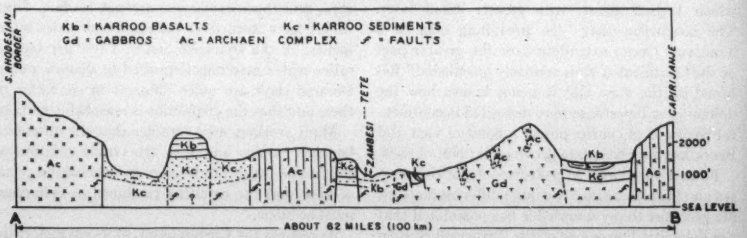

FIG. 6 – Section across the Zambesi Valley with the center at Tete; the Karroo System is definitely controlled by faulting which also controls the flow of the Karroo; some of the faulting is post-Karroo

various diamond mines at Kimberly [Williams, 1932] and in fact in the Orange Free State goldfields, the pre-Karroo surface is shallow, 860 to nearly 2000 ft below the present land surface [*Borchers* and *White*, 1943]. Only in the southern area and southwestern area where the Dwyka is folded and overfolded is there any structural control. In the Transvaal, the Karroo usually lies in comparatively shallow basins on all sorts of older rocks and the shapes of these are reasonably well known from mining and drilling operations.

E. J. Wayland and his staff showed from borehole data that in Bechuanaland the Karroo probably lies in a long trough-like structure but there is no evidence that this is structurally controlled. When the Karroo is considered in the southern part

of Southern Rhodesia, the Zambesi Valley, Portuguese East Africa, and Tanganyika, then I agree that it is practically entirely bounded by faults which are nearly vertical.

Structural depressions such as the Limpopo and Zambesi Valleys—While it is true that the Limpopo and Zambesi Rivers occur in structural depressions these rivers do not flow entirely in valleys which are of structural origin and the two structures are certainly not of the same magnitude. Both rivers have been discussed in some detail by *Wellington* [1955]. In Figures 5 and 6, I show sections of the two rivers, the Limpopo along longitude 30°E and the Zambesi at Tete. It will be seen that the Limpopo Trough is in fact a very wide structure, indeed, but the surface presents only an undulating relief, whereas the Zambesi at Tete, for example, is very marked physical feature. Both these geological sections are the focus of mineralisation by metals such as copper, for example, but whether this is a result of the rift valley faulting, is not known.

Below Pafuri the Limpopo River flows in a broad valley of purely erosional origin, and if any faulting occurs it is either small or of such a nature that it cannot be determined from the exposures of the Kalahari Series beds. The lower course of the Zambesi River at Muturara, for example, is also in a very broad valley but is by a series of complex volcanic plugs, reaching down the river Vila Fontes. Both the rivers have only been mapped in detail in parts and in fact comparatively little is really known about their geology [*Dixey*, 1929]. Brock should have indicated the little that is known geologically of Africa south of the equator, with the exceptions of Southern Rhodesia and the Union of South Africa. As regards the structures at depth even less is known; this particularly applies to the Rift Valley structures. Very little geophysical work has been done and even less drilling, so that the structure at depth is a matter of conjecture and inference. Brock makes no mention of the Great Dyke of Southern Rhodesia, which whether it is regarded as an igneous feature or a trough valley filled with sediments and subsequently metamorphosed into igneous looking rocks, is a very notable vertical tectonic.

The Mozambique Basin—While Brock does not discuss this at all but only shows it on Figure 1, it is important as an example, of how a large basin could develop and what its filling matter could be. Unfortunately very little is known about it except the hard rims of Madagascar and along the western and northwestern limits. It certainly joins up with the East African Rift Valley System, via the Lupata Gulf and Lake Nyasa. My work suggests that the rim between 35° and 40° E and about 17° to 18° S, is in fact a fault one, all supporting Wellington's theory that Madagascar has drifted away from this position, the St. André Spur in Madagascar fitting into the Lupata Gulf.

Kuenen (1950, p. 119) says:

"Matters are complicated by the fact that the floor of the oceans is not a horizontal surface. Inspection of a chart showing the depths discloses a number of basins with comparatively uniform floors, all lying at depths of 5000 to 6000 meters. These are separated from each other by ledges and island festoons and submarine platforms that are isostatically in equilibrium."

While Kuenen is dealing with true oceans in this statement much the same can be applied to the seas, and in fact that is how I conceive the dolomitic limestones to have been formed in Southern Africa. Thus the 10,000 ft of Otavi dolomite may have been formed in an epicontinental trench in comparatively shallow water but sinking under the weight of sediments. Kuenen (p. 97) considers that the oceans start at the 200 m line and he calls the Mediterranean an Inland Sea.

In my new geological maps of Mozambique, I have shown in fact that the old granite and basement complex contacts with the Karroo sediments in Swaziland, and the eastern Transvaal is in general a fault one. Unpublished geological maps by the late Mr. Scoggins show the importance of vertical faulting in a north-south direction. Up to latitude 20°, my 1:1,000,000 geological map of the southern part of Mozambique, brings out the importance of vertical tectonics of rift valley dimensions. The sides of the basin may, therefore, be of very steep nature over the greater part of the western limits of the basin. In the central part of Mozambique, there is the Inhaminga Anticline, proved by oil exploration and it must be noted that in this area over 2000 ft of sediments of a desert environment were encountered, calling for some notable vertical tectonics. This is not surprising as this lies in the projection of the Nyasa Rift. The Zambesi Valley is complicated by rifting about normal to this. Very little has been published about the floor of the Sul do Save part of Mozambique, (32° to 36° E, and 20° to 25° S), but it cannot be expected that the rhyolites and basalts which are the most easterly outcrops of hard rocks form a smooth sea floor. As this area has been thoroughly studied geophysically for oil, and some drilling has been done, its structure should be known soon.

Brock's Models—I feel that neither of Brock's models is a good one. His model (p. 1049) of the

breaking of quartzite cores is certainly not a common one to geologists, except those working on the massive quuartzites in Africa, and while Brock only suggests that the analogy is useful, namely, that the casual blow of a hammer tends to produce core which is a function of the diameter, I feel that it is not a good one. His other analogy (p. 1052) is also open to question. Surely as fluids of the nature of tooth paste are incompressible, the length of ribbon (of uniform cross section) is an exact if complicated function of the compression of the tube. There is no loss of volume anywhere; the more one squeezes the tube the more is extruded. This is a function of the diameter of the tube which for the greater part of its dimensions is of uniform cross-section.

Africa offers a great scope for the study of structural geology but a vast amount of field mapping remains to be done, not only in the thinly populated territories such as Angola, Bechuanaland, Mozambique, Nyasaland, Northern Rhodesia, Tanganyika etc., but also in the better mapped areas of the Union of South Africa and Southern Rhodesia. While mining companies have done a great deal of geophysical work in the Orange Free State and the Witwatersrand areas, very little is known at depth of the Karroo Basin in the Great Karroo. The same applies to the Bushveld Complex and the Great Dyke, and the complicated orogenic belts of the Murchison Range and the Messina Areas. Unfortunately these areas have been largely planed off by erosion, so that the structures at depth must be inferred from surface outcrops and what mining has taken place. Such folded and overfolded structures are far more common than is generally believed and very large orogenic belts can be traced in eastern Niassa (Northern Mozambique).

I think that Brock should now carry the problem further by dealing with some of the points he has raised, in greater detail. Of particular importance I think are the possible connections of vertical movements and mineralization and the elucidation of the nature of vertical movements, first by geophysical methods and later by deep drilling to depths of over 5000 feet, perhaps in the case of features such as the Great Dyke to over 10,000 ft.

Work of the nature published by *Willmore* and others [1952] is of the greatest value in elucidating the structure of the Earth's crust at depth, but even when supplemented by magnetic and gravimetric work, can never give more than a general interpretation of the Earth's crustal structure. Such exploration work can delimited the areas for detailed exploration by means of drills, and no better use could be made of such methods than in the areas of vertical tectonics. Exploration by drills to over 10,000 ft depth would not only lead to a better understanding of vertical or near vertical movements but should show whether such vertical movements have led to connections with deep masses, such as the ore magmas, if they exist. I think that Brock has very opportunely raised the subject, even though I disagree with some of his details.

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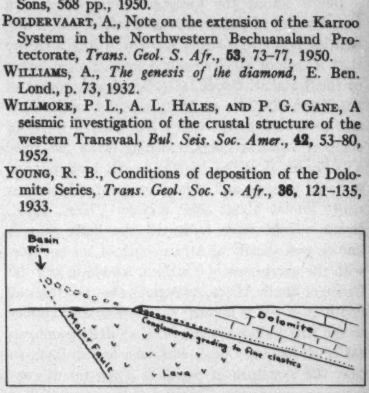

Fig. 7 – Diagrammatic section of rim of Dolomite Basin

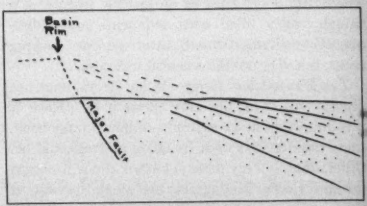

Fig. 8 – Diagrammatic section of rim of upper Witwatersrand Basin

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B. B. Brock (Anglo American Corp. of South Africa, Ltd., Johannesburg, South Africa, Author's Closure)—Regarding the Transvaal Dolomitic Basin and Karroo Basin, clear evidence was presented to show why I consider the dolomite basin is a restricted continental basin. Figures 7 and 8, are now added in case the description was inadequate. It is satisfactory that Bosazza agrees that we are not dealing with oceanic deposits. Apart from the question of limits of deposition, his contribution does not conflict with but rather supplements mine. If we are in fact dealing with even a limb of an ocean, vertical tectonics must have reached even greater heights and depths than are now readily apparent.

The structural and stratigraphical data in the sections were obtained from an abundance of drilling. Had drilling been confined to the eastern half of Figure 7, no evidence of structural control would have been revealed. The absence of evidence of structural control in the Karroo is in no way surprising. The sedimentary overlaps in the final filling of a basin no doubt have done much to obscure the actual lip. My contention is that the 15,000 ft of Karroo shallow-water sediments demand a sinking floor for their accommodation; the whole process is dependent on structure. It not only involves vertical tectonics. it *constitutes* vertical tectonics. In discussing my models, Bosazza says that very little is known of the Karroo at depth. I venture to suggest that the pre-Karroo 'erosional surface' involved some quite active structural geology to provide a raised source for the tremendous volume of sediments being fed from the margins. Is it necessary for this buried feature to be found before suspecting its presence? Perhaps it has not been found because no one has looked properly. Tectonic rims are recorded here as a solemn prediction.

Regarding structural depression, there is nothing under this heading to cause an argument. If I have refrained from comment on how much of Africa is unknown, that should be implicit in my suggested manner of attack. The Great Dyke is a subject in itself, a highly unusual (hence a more than ordinarily controversial) manifestation of vertical tectonics.

Regarding the Mozambique Basin, the shape of the partial outline of this allows of the completion of its perimeter of the same sort of size and shape as the Kalahari and Congo Basins. This is the best sort of evidence available to controvert the suggestion of Madagascar having drifted away from Africa. The whole concept of vertical tectonics is quite incompatible with that of continental drift.

Concerning models, core splitting may not be common experience, but any geologist should be sufficiently familiar with quartzite to be able to visualize the analogy. The point is that any homogeneous brittle material will shatter into fragments of similar sizes under similar stresses. In other words, 'nature works true to scale.'

Rather than taking further unorthodox liberties with the toothpaste tube, I shall acknowledge that it must not be a good analogy if I have not made my point clear. 'Folded and overfolded structures are far more common than is generally believed.' This statement reveals a certain bias. It all depends on one's experience and background as to whether one is more impressed by the rigid blocks of the crust or by the hinge zones that enclose them. Economic geologists may see more of hinge zones than anything else. I have tried very hard to get the two into their proper perspective. In the Archaean the rigid blocks are small, the hinge zones discontinuous and diverse in their trends and narrow in width. The hinge zones, like their respective rigid blocks, have grown bigger with the passage of time, their trends stronger, the contained sediments thicker and the compression correspondingly intense. That at least is my contention.

I endorse Bosazza's plea for more field work, but as an economic geologist I would hesitate to recommend 10,000-ft or 5000-ft boreholes for the sole purpose of elucidating the nature of vertical movements.

In closing I would like to thank Bosazza for contributing to the discussion and to intimate in the most delicate manner that for the most part his discussion deals with subsidiary details, not altering the general picture, which in my opinion constitutes a framework upon which to build. Building upon this framework is in effect what he is doing.

Discussion of "Evaporation from and Stabilization of Salton Sea Water Surface"

BY HARRY F. BLANEY

[*Trans.*, **36**, 633–640, 1955]

Carl Rohwer (Colorado A and M College, Fort Collins, Colorado, received December 23, 1955)—The rise and fall of the Salton Sea can be explained on the basis of inflow and evaporation. This fact is clearly demonstrated by the author. As shown in Table 7, there was an excess of inflow over evaporation of 823,400 ac ft from 1945 to 1953, and during this period the level of the sea rose from −240.5 to −236.2, a total of 4.3 ft. However, the excess inflow of 823,400 ac ft should have caused a rise of only 3.9 feet on the basis of the average surface area of the Salton Sea in that range of elevation. This discrepancy can be explained by the fact that neither the inflow nor the evaporation can be precisely determined.

Although the main inflow, which occurs through the New and Alamo rivers, can be measured with reasonable accuracy, there are several small streams discharging into the Sea, which may add varying amounts to the inflow. These streams are usually dry, but they may contribute large quantities of water in times of flood after torrential rains which occasionally occur in the foothills. The inflow from these sources must be estimated.

There is no direct method of measuring the evaporation from the Salton Sea. The various methods which have been used to determine the evaporation have yielded fairly consistent results, but an error of only a few inches in the annual evaporation over the period of years reported, would amount to a foot or more in estimated change in the water level. The variation in the pan evaporation at the three stations used by the author, which amounts to nearly 24 inches, is an indication of the difficulty encountered in making an accurate estimate of the evaporation. Had the evaporation stations been located at different points on the shore of the Sea, widely different rates of evaporation might have been observed.

Furthermore, the factor for correcting pan evaporation into evaporation from Salton Sea is not definitely known. In making his computations, the author converted the screened pan evaporation into the equivalent Weather Bureau Class A land pan evaporation and then applied a coefficient of 0.60 to convert the latter values into the evaporation from the Sea. Had the author converted the screened pan evaporation directly to lake evaporation by applying the generally adopted coefficient of 0.98 [*Young*, 1947], a much higher evaporation would have resulted. However, if the values obtained in this manner had been used, the evaporation would have exceeded the inflow, which obviously is not the case because the water level rose 4.3 ft.

The author used the factor 0.60 for converting Weather Bureau pan evaporation into lake evaporation, whereas the writer [*Rohwer*, 1931] found the conversion factor to be 0.70, based on tests in Colorado and elsewhere. *Young* [1947] in California found the factor to be 0.77. Recent tests on Lake Hefner in Oklahoma [*U. S. Geological Survey*, 1952], in which Class A pan records were compared with the Lake evaporation, showed that the conversion factor is 0.70. This factor is based on monthly records from May 1950 to August 1951. The factor 0.60 was obtained by the author from tests on Silver Lake in the Mojave Desert. All these conversion factors are based on carefully conducted observations, but the largest value is nearly 30 pct greater than the smallest. If no data had been available for Silver Lake, a much higher evaporation from Salton Sea would have been obtained. The difficulty in determining the true value of the evaporation is apparent.

It is interesting to note that the total amount diverted from the Colorado River for irrigation of the Valley in 1951, was 3,500,000 ac ft and the measured return flow from the Imperial and Coachella Valleys (see Table 7), was 1,285,000 ac ft. More than one third of the water applied for irrigation was not used by the crops but was added to the Salton Sea either as waste or drainage water. It is recognized that the high salt content of the soil and also of the irrigation water, make it necessary to use excessive quantities of water for irrigation and leaching. However, it would seem that a more careful control of these uses might materially reduce the inflow to the Salton Sea and thereby decrease the area of good land that will ultimately have to be covered by water before the level of the Sea will be stabilized.

N. J. Cochrane (Alliance House, Caxton St., Westminster, London, S.W. 1, England, received December 27, 1955)—I have made a study of a sample of evaporation data from various parts of world, the sample amounting to 80 sites. No evaporimeter smaller than the U. S. Class A pan has been considered. Although the data are not all believed to be accurate, I deduced a formula of the following form to relate open-water evaporation and the climatic data most likely to be available.

$$E_e = \frac{T^2}{100}\sqrt[3]{\frac{U+3}{20H_r}} \times \left(\frac{60}{H_r T}\right)^{0.8}$$

where

E_e = Open-water evaporation in inches per annum
T = Mean annual temperature, °F
U = Wind speed in miles per hour at ten meters
H_r = Relative humidity

The writer does not consider that data from evaporation pans is an entirely satisfactory method of calculating the evaporation from a large body of water and unfortunately there are very few true water budgets available. This makes the Salton Sea data of special interest to hydrologists.

By water-budget measurement Blaney gives the average evaporation from Salton Sea in 1949 and 1950 at 68.5 inches per annum with little change from year to year. From climatic data for three stations kindly supplied by Blaney my formula indicates a value of 62 inches per annum. Other water-budget comparisons and one good floating pan comparison are summarised in Table 8. The correlation to date is within ±10 pct which is reasonable enough if the type of data available is borne in mind.

Harry F. Blaney (Agriculture Research Service, USDA, Los Angeles, Calif., Author's closure)—The frank discussion by Carl Rohwer is appreciated as it affords an opportunity to answer questions which might arise in the minds of other readers of this paper.

The discussor explains the difference between the rise 4.3 ft of Salton Sea shown in Table 7 to a computed rise of 3.9 ft (based on average surface area) by the fact that neither the inflow nor the evaporation can be precisely determined. This statement is correct; however, the average area of the Sea can not be accurately determined, and thus it is also a factor to be considered. The difference of 0.4 foot in elevation is not significant since a single storm has raised the surface level as much as 1.5 ft.

TABLE 8 – *Evaporation comparisons*

Site	Evaporation per annum	
	Water budget	My calculation
	inch	inch
Lake Hefner	52	55.8
Salton Sea	68.5	62
Zugersee	30.5	30.3
Staines Reservoir	37	34
Assuan Reservoir	101.8	109.8

TABLE 9 – *Estimated Salton Sea evaporation*

Year	Temperature[a]	Humidity	Wind velocity	Evaporation Salton Sea[b]
	°F	pct	mi/hr	inch
1949	68.5	57	3.53	67
1950	70.2	52	3.12	74

[a] Mean annual of Stations 1, 2, and 3 at Salton Sea (shown in Figure 1)
[b] Computed by $E = KC = 0.0165\ C$.

The statement, "Had the evaporation stations been located at different points on the shore of the Sea, widely different rates of evaporation might have been observed" is not correct when applied to the Salton Sea study as the location of these stations were selected only after careful consideration was given to the shape of the Sea and prevailing winds. It should be noted that Station 2 gives average evaporation, Station 1 is affected by dry-air movement from desert lands and Station 3 is influenced by movement of moist air after it has passed over Salton Sea.

Although the coefficient 0.98 is generally used to convert screen-pan evaporation to lake evaporation when installed under normal exposure and climate, this value is not correct for extreme desert conditions. The ratio between evaporation from Silver Lake and from the screen pan was 0.65 [*Young* and *Blaney*, 1941]. If this coefficient were applied to the average screen pan evaporation shown in Table 3 for Station 1 the evaporation from Salton Sea would average 72.6 inches for the 1948–50 period.

Rohwer questions the use of a coefficient 0.60 for the Class A Weather Bureau pan under desert conditions. A subcommittee of the American Society of Civil Engineers (Scobey, Houk, Rohwer, and others, 1934) after careful consideration recommended a coefficient of 0.70 for a Class A land pan and reasonable range in coefficient from

0.60 to 0.82. The observations at Silver Lake in the Mojave Desert were carefully made and the pan exposure was similar to those adjacent to Salton Sea. Although the Lake Hefner studies [*U. S. Geological Survey*, 1952] indicate a coefficient of 0.70 they covered two summer periods and only one winter period. The climate at Lake Hefner has been classed as subhumid and the rainfall during the last 12 months of the observation period totaled 27.1 inches.

As indicated by Rohwer a more careful control of water used for irrigation in Imperial and Coachella valleys would reduce the inflow to Salton Sea. However, the American water users have no control of the 150,000 acres of land irrigated in Mexicali Valley in Mexico which drains into the Sea through the Alamo and New Rivers. Also the Colorado River water contains approximately one ton of salt per acre foot; thus excessive water is required for irrigation to maintain a proper salt-balance in these areas.

The interesting discussion by N. J. Cochrane is appreciated and adds to information on evaporation from lakes and reservoirs. The formula presented by Cochrane, while rather lengthy, includes the principal factors affecting evaporation from water surfaces. However, attention is called to the fact that wind speeds in United States are usually measured at either higher or lower elevations above ground surface than ten meters. Wind movement at U. S. Weather Bureau Class A evaporation stations is measured at about one foot above the water surface.

Some years ago the author developed a formula for estimating evaporation in the Pecos River basin in New Mexico from mean temperature, humidity, and daytime hours for average velocities of three to five miles per hour measured about one foot above the water surface [*Blaney* and *Morin*, 1942]. When used to compute annual evaporation this formula was simplified to an expression; $E = KC$ = evaporation in inches; where C = 1.03 T (114-H) = annual index; K = annual empirical coefficient; T = mean annual temperatures (F°), and H = mean annual humidity. The annual value of K for lake surfaces determined in the Pecos River investigation was 0.0164 and from measurements of evaporation, temperature, and humidity at Silver Lake as 0.0165 [*Young* and *Blaney*, 1941]. Using a K value of 0.0165 the estimated evaporation from Salton Sea is computed in Table 9.

Corrigendum—In the published paper, page 638, the last column of Table 4 should not have an indication of inch as the unit. The values are dimensionless ratios.

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Notes and Personalia

Notes

RECENT DEVELOPMENTS IN IGY—The great international program of cooperation in science and research relating to the physics of the Earth, commonly referred to as the International Geophysical Year, has developed amazingly from its inception back in 1950 or 1951 and will take place in the eighteen-month interval from July 1, 1957 to December 31, 1958. (The purpose of the eighteen-month interval is to insure twelve months of co-incidental data from all stations and areas involved in the program.) This has evolved from the International Polar Years, the First of which was held in 1882–1883, which brought about extensive international cooperation that resulted, among other things, in the establishment of the magnetic field of the Earth. The Second Polar Year was held in 1932–1933, and one of the long-standing results of the international collaboration was the establishment of a network of meteorological stations over the entire northern

hemisphere that has permitted synoptic studies of meteorology on a world-wide basis. Because of the character of the plans for this third effort in international cooperation, it was called the International Geophysical Year, as the plans involved not only polar areas but all areas of the Earth, concentrating especially on the unknown Antarctic and vast other areas of the Earth from which little geophysical data have been collected. The work may be broken down into thirteen major phases, eleven of which are subject matter as follows: Aurora and Airglow, Cosmic Rays, Geomagnetism, Glaciology, Gravimetry, Ionospheric Physics, Longitude and Latitude, Meteorology, Oceanography, Seismology, and Solar Activity. The twelfth, referred to as World Days or World Intervals, has to do with days especially set up for intensified observational work. Certain special days or intervals will be established during the progress of the Geophysical Year when some unusual phenomenon, such as a magnetic storm, occurs. The thirteenth is a study of various phenomena by means of rocketry and satellites, and thus this is a device of instrumentation rather than a field of study.

Some fifty nations are subscribing to the cooperative effort, and those taking part in specific programs are set forth in Table 1. The detailed programs have been outlined for various countries and for various fields in documents of the IGY and have recently been summarized in a report of the U. S. National Committee for IGY that is very extensive. This may be consulted in the office of the International Geophysical Year; and persons interested in a particular phase may receive detailed word concerning that phase from the office of IGY at 2101 Constitution Avenue, N. W., Washington 25, D. C.

In the last few months there have been a number of international conferences, one relating to the Arctic was held in Stockholm, May 22–25, 1956; one relating to the Western Hemisphere at Rio de Janeiro, July 16–20, 1956; one on the Antarctic in Paris, July 30–August 3, 1956; and one relating to Eastern Europe in Moscow, August 20–25, 1956; with the general meeting of the International Committee (CSAGI) held in Barcelona, Spain, September 10–16, 1956. At the meeting in Barcelona further plans were worked out for cooperation by the various countries in all phases, and especial attention was given to problems of dissemination of data and information including the declaration of special days or world intervals. Plans were also worked out to fill in the gaps in the coverage of observations and for the establishment of three International Data Centers, one of which will be in the United States. United States plans for the satellite program were outlined in detail.

With regard to specific programs of the United States, the one on Rocketry and Satellites has received perhaps the greatest attention in the press. This program has many phases. The Fort Churchill Rocket-Launching Platform was constructed in Canada by cooperation between Canadian and American scientists on the invitation of Canada. It was recently dedicated and the first rocket was launched. At the same time, "Project Rockoon" (a balloon-launched rocket program) of the Office of Naval Research has been making preliminary tests off the coast of California. The recently completed series of upper-atmosphere experiments were made for the purpose of obtaining data on the strength of x-ray and ultraviolet radiations from solar flares, and ten flights were undertaken as preliminary to the main program during the International Geophysical Year. The rocket-balloon combinations were launched from the U.S.S. *Colonial* in the latter part of July. Under this, the rocket is launched from a helium-filled plastic balloon 72 feet in diameter, after the balloon has attained an altitude of 60,000 to 80,000 feet. Deacon rockets about 12 feet long are equipped with instruments for the measurement of the desired atmospheric characteristics and elements.

Currently tests are being made of elements of the Earth-satellite vehicle at the test center at Cocoa Beach, Florida; but it is not planned that test vehicles will project a satellite into an Earth-circling orbit. The launching vehicle will be a three-stage rocket about 72 feet long, with the third stage propelling the satellite with a velocity of 18,000 miles per hour, a speed that will counteract the Earth's gravitational force.

In connection with the satellite program, extensive observation plans are under way both by scientific personnel and by volunteers. Under the volunteer optical program called "Moonwatch," on one evening, the date to be known only a few days in advance, all volunteer observers will man specific stations to report what, if anything, they see. Reports will be made to the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts. Volunteers interested in aiding this program should write to the Observatory in Cambridge.

The scientific results of the Rocketry and Satellite programs should give us much information on atmospheric structure, winds, solar ultraviolet and x-rays, airglow, aurora, ionospheric charge densities, chemical and ion composition, magnetic field, and cosmic rays. In addition, the satellite program will give detailed information on cloud cover of the Earth, meteoric impacts, galactic radiation, information useful for geodetic and mapping observations, and information concerning the gravity field of the Earth.

The Arctic Program of the United States is covered concisely in the *News Report* of the National Academy of Sciences for September–October, 1956, pages 73–76. In connection with the Arctic program, the United States Government has offered to enter into an agreement with the U.S.S.R. which would permit Soviet and American planes to fly between Nome, Alaska and Murmansk in an effort to get a more comprehensive photographic record of the polar icepack and its changes. Detailed information bearing on the American program in the Antarctic is covered in AGU's Monograph Number 1 entitled "Antarctica in the International Geophysical Year." The establishment of the U. S. bases in the Antarctic is now in progress during this Antarctic summer, and those remaining at the end of this Antarctic summer will stay until the beginning of the succeeding summer. One station is now under construction at the South Pole. The scientist in charge will be Paul A. Siple, who expects to spend the coming Antarctic winter at that location.

In order that the information gathered under this program of international cooperation may be available to scientists all over the world, three complete data centers are being established, one of which will be in the United States. Under present plans, this center may have several branches with particular subject

TABLE 1 – *Table showing participation in specific IGY programs*

Countries	Program												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
Argentina	×	×	×	×		×			×			×	×
Australia	×	×	×	×	×	×	×	×	×	×	×	×	×
Austria	×	×	×	×	×	×	×	×			×	×	
Belgium	×	×	×	×								×	
Bolivia	×	×	×		×		×	×	×			×	×
Brazil		×	×		×		×			×		×	×
Bulgaria		×	×				×	×				×	
Canada	×	×	×	×	×	×	×	×	×	×	×	×	×
Chile	×											×	
Chinese Peoples Republic	×	×	×		×	×	×	×				×	
Colombia									×				
Czechoslovakia	×	×	×	×	×	×	×	×			×	×	×
Denmark	×	×	×	×	×	×	×	×	×	×		×	
Egypt	×	×	×		×	×		×			×	×	×
Ethiopia			×									×	
Finland	×	×	×		×			×		×		×	
France			×	×					×		×	×	
East Germany		×	×			×	×	×	×	×		×	×
Hungary		×	×									×	
Iceland	×	×	×	×	×	×	×	×	×	×		×	
India	×	×	×	×	×	×	×	×	×	×		×	
Indonesia		×	×									×	
Iran			×				×					×	×
Ireland	×	×	×	×		×						×	
Israel												×	
Italy	×	×	×	×	×	×	×	×	×	×	×	×	×
Japan	×	×	×	×	×	×	×	×		×	×	×	×
Mexico	×	×	×	×	×	×	×	×	×	×		×	×
Mongolia												×	
Morocco												×	
The Netherlands		×	×		×	×	×	×		×			
New Zealand	×	×	×	×	×	×	×	×	×	×		×	×
Norway	×	×	×	×	×	×	×	×	×	×		×	
Pakistan		×	×									×	
Philippines	×	×	×		×	×	×	×		×		×	
Poland									×				
Portugal			×										
Rumania												×	
South Africa		×	×		×							×	
Spain												×	
Sweden	×	×	×	×	×	×	×	×	×	×		×	
Switzerland		×							×		×		
U.S.	×	×	×	×	×	×	×	×	×	×	×	×	×
U.S.S.R.	×	×	×	×	×	×	×	×	×	×	×	×	×
United Kingdom	×	×	×	×	×	×	×	×	×	×	×	×	
Yugoslavia		×	×			×						×	

I. World Days; II. Meteorology; III. Geomagnetism; IV. Aurora and Airglow, V. Ionospheric Physics; VI. Solar Activity; VII. Cosmic Rays; VIII. Longitude and Latitude; IX. Glaciology; X. Oceanography; XI. Rocketry and Satellites; XII. Seismology; XIII. Gravimetry.

matter being handled at a particular branch. It is anticipated that the data gathered will be source material for geophysical scientists for years to come, and it is important that these data centers be adequately developed in order that the basic data are readily available.

The U. S. National Committee holds periodic meetings, and in the organization of the activity the work is broken down into panels similar to the outline shown in Table 1. These panels are at work arranging the final stages of their program plans and initiating their implementation.

In connection with this great undertaking, there is still some need for scientific personnel for certain phases of the work. These personnel are engaged in most instances by the numerous organizations, governmental and other, cooperating in the work of the International Geophysical Year.

RESEARCH POSITIONS AVAILABLE ON U. S. IGY PROGRAM—The Geophysics Research Directorate of

the Air Force Cambridge Research Center, 415 Summer Street, Boston 10, Massachusetts, is recruiting scientists for work on the Aurora and Airglow Antarctic Program of the IGY. Interested persons should write to the Chief Scientist of the Aurora and Airglow Program at the address mentioned above. It is likely that scientists are sought for work on other phases of the broad IGY program, but because of the fact that work is being carried out by very diverse groups, both governmental and other, no central clearinghouse has been set up for the receiving of applications.

TRANSLATION OF FOREIGN LITERATURE—The National Science Foundation has announced a grant of $57,860 to the American Institute of Biological Sciences for the purpose of translating three Russian biological journals to English. Subscriptions to these journals are being accepted by the Institute (2000 P Street, N.W., Washington, D. C.), the payments of which will be used to help extend the work done under the grant. Another grant of $20,350 has been given to the Special Libraries Association to operate a Scientific Translations Center to collect, announce, and sell photocopies of scientific translations. This Center is located at the John Crerar Library in Chicago. A grant of $11,700 has been made to the Midwest Inter-Library Center in Chicago, which will use the funds to acquire 700 to 800 serial publications of chemical interest that are deemed ordinarily hard to get.

Plans are likewise under way for similar work to be undertaken on other scientific publications.

POSTDOCTORAL RESIDENT RESEARCH ASSOCIATESHIPS PROGRAM—The National Academy of Sciences has announced the program of Postdoctoral Research Associateships supported by the Argonne National Laboratory, the National Bureau of Standards, the Naval Research Laboratory, and the Oak Ridge National Laboratory. These are awarded to citizens of the United States, and the applicant must produce evidence of training in one of the fields listed that represent the equivalent of a doctorate and must have demonstrated superior ability for creative research. Stipends range up to $7035 a year. Applications must be filed with the Fellowship Office of the National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington 25, D. C. on or before January 11, 1957.

CONTINUATION OF FELLOWSHIP PROGRAM OF THE NATIONAL SCIENCE FOUNDATION—The predoctoral and postdoctoral program of fellowship awards which has now extended over several years has been announced for 1957. The project is being handled by the Fellowship Office of the National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington 25, D. C. The applications for predoctoral fellowships must be filed by January 7, 1957, and postdoctoral by December 24, 1956.

SCIENCE FACULTY FELLOWSHIP PROGRAM OF THE NATIONAL SCIENCE FOUNDATION—A new program of Faculty Fellowships has been announced by the Foundation, with about 100 awards to be made. These are available to citizens of the United States with a baccalaureate degree or equivalent who have demonstrated ability and special aptitude for science teaching and advance training, have taught at the collegiate level as a full-time faculty member for not less than three years, and intend to continue teaching. The award will be adjusted as closely as possible to the regular salary of recipients, but the total support will not exceed $10,000 a year except for allowances for travel and other expenses associated with the fellowship study. Applications should be filed with the National Science Foundation, Washington 25, D. C. not later than January 14, 1957.

CIVIL SERVICE EXAMINATIONS FOR PHYSICAL SCIENCE POSITIONS—The Civil Service Commission has recently announced an examination to fill physical science positions in the Potomac River Naval Command and the Engineer Center of the U. S. Army at Fort Belvoir at entrance salaries ranging from $4480 to $11,610 per year. Applications should be filed with the Board of Civil Service Examiners for Scientific and Technical Personnel, Potomac River Naval Command, Washington, D. C. as soon as possible. No closing date has been announced.

INTERNATIONAL COOPERATION IN URANIUM EXPLORATION—The Atomic Energy Commission has approved plans for a program of extending cooperation with friendly nations in the field of uranium exploration. The plan involves assistance from the United States to these nations by giving them access to uranium geology and exploration techniques, encouraging geologists, geophysicists, and others in interested countries to visit the United States to study uranium deposits and exploration and laboratory methods, and permit AEC scientists to make brief visits to other nations to aid in the use of the techniques.

NEW NUCLEAR RESEARCH CENTER IN THE U.S.S.R.—The U.S.S.R. has established its Joint Nuclear Research Institute at the small town of Pubna, about 95 miles northeast of Moscow, with buildings and equipment to cost about $125,000,000. This was established by the U.S.S.R. and 11 satellite countries and was officially opened in September. The new center is to conduct high-energy research and provide research facilities for training nuclear physicists from the member states and will not involve secret work.

RADIO SIGNALS FROM THE PLANETS—For some time radio signals have been received from various points in outer space, but only this year was it announced by the Naval Research Laboratory that radio signals have been detected as being emitted by the Planet Venus. During the time that Mars was at its closest point to the Earth, radio signals emitted by Mars were also observed.

INTERNATIONAL ASSOCIATION ON QUATERNARY RESEARCH TO HOLD ITS CONGRESS IN MADRID AND BARCELONA—The Fifth International Congress of this Association will meet in Madrid and Barcelona, Spain, in September and October, 1957. Persons interested should write to M. L. Solé Sabarís, Instituto Geológico, Universidad, Barcelona, Spain.

FALL MEETING OF THE NATIONAL ACADEMY OF SCIENCES—The fall meeting of the National Academy of Sciences was held in Washington, D. C., November 8

to 10, 1956. Included in the program were a number of papers bearing on geophysics, including one by Irving Friedman and Alfred C. Redfield entitled "Deuterium-Hydrogen Fractionation during Freezing of Water;" another by Franklin E. Roach, "A Synoptic Study of the Airglow;" one by Thor N. V. Karlstrom, "Radiocarbon-based Pleistocene Correlations and Worldwide Climatic Change;" one by Howard E. Tatel, "The Structure of the Earth's Crust from Gravity Measurements; and one by T. P. Thayer, "Some Relations of Later Tertiary Volcanology and Structure in Eastern Oregon."

RESUMPTION OF PUBLICATION OF *Beiträge zur physik der Atmosphäre*—The resumption of publication of this periodical began with Volume 29, Number 1, in 1956. Orders originating in this hemisphere should be sent to Walter J. Johnson, Inc., 125 East 23rd Street, New York 10, New York. An editor from the United States has been designated. This is Bernard Haurwitz of the Department of Meteorology and Oceanography of New York University.

NEW PUBLICATION IN PHYSICS—A new monthly journal entitled *Annals of Physics* has been announced by Academic Press to be issued under the editorship of Philip M. Morse, Professor of Physics at MIT. Volume 1, Number 1, is scheduled for release in April, 1957. The *Annals* hopes to provide a medium for the publication of important articles that are internally complete and generally understandable to professional physicists.

NEW INDIAN JOURNAL—The *Journal of Technology*, a half-yearly publication of original contributions in science and technology, is being published by the Bengal Engineering College, P. O. Botanic Garden, Howrah, India. The first issue contains two papers of geophysical interest, the first entitled "On the Flow of a Viscous Liquid between Two Co-Axial Circular Cylinders under a Periodic Pressure-Gradient" by Lakshmi Sanyal; and the second, "Transients in the Records of Seismic Body Waves" by K. N. Banerjee.

SECOND SYMPOSIUM ON ROCK MECHANICS—A second Symposium of the Colorado School of Mines on Rock Mechanics will be held at Golden, Colorado, April 22–24, 1957. The papers of the first Symposium appear in a recent issue of the *Quarterly* of the Colorado School of Mines.

CANADIAN OCEANIC CURRENT SURVEY—The Canadian Meteorological Station on Vancouver Island is planning to launch 15,000 bottles into the Pacific Ocean at points ranging up to 1500 miles from the shore. Those who find the bottles are urged to send information requested in each bottle.

RESULTS OF EXPEDITION CHINOOK—Preliminary results of Expedition CHINOOK of the Scripps Institution of Oceanography, carried out in the north-central Pacific starting in late June, 1956, are now available in a mimeographed release of the Scripps Institution of Oceanography dated October 15. A brief summary is given relating to the seismic studies, coring, topography, hydrographic data, ambient noise measurements, vertical acceleration measurements, and zooplankton. Included is a map showing the course followed.

SECOND SESSION OF THE COMMISSION FOR CLIMATOLOGY, WMO—This Commission of the World Meteorological Organization will meet in Washington, January 14–26, 1957. Reports by the Working Groups on Climate and Health, Climate and Agriculture, Climatological Summaries, Exchange of Historical Weather Data, and other phases will meet at that time. Meetings of the various Commissions and Working Groups of WMO meet in various parts of the world at frequent intervals. Others in progress include Meteorological Telecommunications, to be held in the Canary Islands in mid-January; Regional Association I (Africa) in the Canary Islands in late January and early February; Synoptic Meteorology in March, location undesignated; Aerology in Paris in late June; Instruments and Methods in Paris in late June; Executive Committee in Geneva in September and October; Bibliography and Publications in Paris in October; and Regional Association III (South America) in Caracas in October. Details may be secured by writing to the Secretariat of WMO, Avenue de la Paix, Campagne Rigot, Geneva, Switzerland.

REPORT ON RESEARCH INSTITUTES BY NSF—A report has recently been issued by the National Science Foundation outlining the research and development work of non-profit research institutes and commercial laboratories during 1953. Copies of this may be obtained from the Superintendent of Documents in Washington, D. C., at a price of $.50.

NEW EMPHASIS ON HYDROLOGY IN THE U. S. GEOLOGICAL SURVEY—Reorganization of the Water Resources Division of the Geological Survey has involved the establishment of a new Assistant Chief of the Division for Operations (Raymond L. Nace), an Assistant Chief for Program and Development (Luna B. Leopold), and a new administrative officer. Two field representatives of the Division Chief will be known as Division Hydrologists. These are: Arthur M. Piper for the Pacific area, and George E. Ferguson for the Atlantic Coast area. Two others, one for the Rock Mountain area and one for the Mid-Continent area, will subsequently be designated. Within the Division a new branch has been added, namely, that of General Hydrology, with Charles C. McDonald as Chief. The other three branches are: Ground Water (A. Nelson Sayre, Chief), Surface Water (J. V. B. Wells, Chief), and Quality of Water (S. K. Love, Chief). Carl G. Paulsen is Chief of the Division of Water Resources.

COMMITTEE ON EXTENSION TO THE STANDARD ATMOSPHERE—A joint committee of the U. S. Weather Bureau and the Geophysics Research Directorate of the Air Force Cambridge Research Center has been appointed to extend the standard atmosphere beyond the 20 kilometers now accepted as the U. S. standard. The co-chairmen are Harry Wexler for the Weather Bureau and Norman Sissenwine for the Research Directorate.

METEOROLOGICAL RECORDING DEVICE KNOWN AS THE GRASSHOPPER—At a recent meeting of the British Association for the Advancement of Science, Raymond

Priestley, in his opening address presented a paper entitled "Twentieth Century Man against Antarctica." In connection with this, he announced a new meteorological recording device known as the Grasshopper. It weighs about 200 pounds and can be dropped from an aircraft at any point, and it opens automatically, rights itself on six legs, and records weather conditions, transmitting these in Morse code, giving information on wind speeds and direction, temperature, barometric pressure, and humidity. It works for about 60 days. It is anticipated that this will be used by the British extensively in their Antarctic work in connection with the IGY.

Personalia

G. CHRISTIAN AMSTUTZ, Petrologist with the Cerro de Pasco Corporation at La Oroya, Peru, has accepted a position as Associate Professor of Geology at Missouri School of Mines and Metallurgy.

J. CL. DE BREMAECKER has returned to his duties as Geophysicist at the Institute for Scientific Research in Central Africa, Bukavu, Belgian Congo, after spending a year at the Lamont Geological Observatory of Columbia University.

GABOR DESSAU of Italy is on a UNESCO assignment to the Israel Institute of Technology in Haifa, working on the establishment of a Mining Engineering Department. It is anticipated that he will remain there until the fall of 1957. He recently attended the Geological Congress in Mexico.

ROBERT C. FITZPATRICK has left his work at the Air Force Cambridge Research Center and taken up duties as a Research Associate with the Engineering Research Institute of the University of Michigan.

DAVE FULTZ of the University of Chicago has been given a senior postdoctoral fellowship award by the National Science Foundation to study in England, Sweden, and Norway.

GEORGE GAMOW has left his position as Professor of Physics at the George Washington University in Washington, D. C., and taken up duties as Professor of Physics at the University of Colorado. He has recently been named the recipient of the Kalinga Prize of UNESCO and in a brief ceremony at the United Nations Headquarters was recently given the award which includes an honorarium of 1000 pounds sterling.

HERBERT HOOVER, JR., Undersecretary of State, has been designated as the recipient of the Hoover Medal, which is a joint award of the four Engineering Founder Societies. The medal is named in honor of Herbert Hoover, father of the present recipient, and is awarded by the engineers to a fellow engineer for distinguished public service.

FINLEY B. LAVERTY, Chief Hydrologic Engineer of the Los Angeles Flood Control District, has been elected a Director of the American Society of Civil Engineers.

PAUL B. MACCREADY, JR., President of Meteorology Research, Inc. in Pasadena, California, has won the International Glider Competition held in France in July, 1956.

JEROME NAMIAS, Chief of the Extended Forecast Section of the Weather Bureau, has recently returned from a tour of various meteorological centers in Europe. The trip was undertaken with the aid of a Rockefeller Public Service Award and included a sojourn of about six months at the International Institute of Meteorology in Stockholm.

NORRIS W. RAKESTRAW, Professor of Chemistry at Scripps Institution of Oceanography, has been given the Scientific Apparatus Makers Award for his outstanding service to teachers of chemistry and chemical engineering.

C. WARREN THORNTHWAITE, Director of the Institute of Climatology at Centerton, New Jersey, has recently been appointed advisor to UNESCO's program in desert research. He will serve on the Advisory Committee. Dr. Thornthwaite replaces Gilbert F. White, who served during the previous triennium. The semi-annual meeting of the Committee was held at Canberra in Brisbane, Australia, in October, 1956.

NORMAN LEVI BOWEN, Petrologist of the Carnegie Institution of Washington, retired, died September 11, 1956, at the age of 69. He was born in Kingston, Ontario, Canada. He took his baccalaureate and master's degrees from Queen's College and was awarded an honorary degree in 1941. He took his doctorate at Massachusetts Institute of Technology in 1912 and was awarded an honorary doctorate by Harvard in 1936 and by Yale in 1951. His work as Petrologist at the Carnegie Institution began in 1912, continuing until 1918, then resuming for the interval from 1920 to 1937 and 1947 until his retirement in 1952. From 1918 to 1920, he served as Professor of Minerology at his alma mater; and from 1937 to 1947, he was Professor of Petrology at the University of Chicago, being Chairman of the Department for the years 1944–1947. In addition to his honorary degrees, he was the recipient of a number of medals, including the Bigsby Medal of the Geological Society of London in 1931, the Penrose Medal of the Geological Society of America in 1941, the Miller Medal of the Royal Society of Canada in 1943, the Roebling Medal of the Minerology Society of America in 1950, and others. He was a member of the National Academy of Sciences. He had been a member of the American Geophysical Union since 1920 and served as Vice President of the Section of Volcanology from 1924 to 1926.

BENARTHUR C. HAYNES, Meteorologist and Consulting Engineer for the Research Division of Lockheed Aircraft Company at Burbank, California, on leave from the U. S. Weather Bureau, died suddenly April 29, 1954, at the age of 44. He was born in Santa Fe, New Mexico, and received his baccalaureate degree from California Institute of Technology in 1932. He

took his master's degree in 1933 in Mechanical Engineering, and a second master's degree in Meteorology in 1936. In 1936, he took up work in charge of the Meteorology Department of the Boeing School of Aeronautics in Oakland and three years later went into the service of the U. S. Weather Bureau, nonetheless serving for various periods in capacities for other groups such as the Civil Aeronautics Board as an Air Safety Specialist in 1941–1942. He was one of the few persons who had flown over both poles. He had been a member of AGU since 1937.

GEORGE MARTIN LEES, Chief Geologist, Anglo-Iranian Oil Company, retired, died January 25, 1955, at the age of 56. He was born in County Louth, Ireland, pursued studies at St. Andrews College in Dublin, where he completed his work in 1915, immediately thereafter entering the Royal Military Academy at Woolwich, following which he served in World War I. From 1919 to 1921, he was in Iraq as one of the representatives of his government working among the turbulent tribes of Southern Kurdistan. In 1930, he was appointed Chief Geologist of the Anglo-Iranian Oil Company, which post he held until 1953 when he retired. He received many honors and awards, and in 1943 the Geological Society of Great Britain awarded him the Bigsby Medal, and in 1948 he was elected a Fellow of the Royal Society. Following his retirement from the Anglo-Iranian Oil Company, he continued work as Geological Advisor to various oil companies. In the spring of 1954, he was awarded the Sidney Powers Memorial Medal by the American Association of Petroleum Geologists. He had been a member of AGU since 1947.

WALTER BENJAMIN ZERBE, Chief of the Currents and Oceanography Branch of the U. S. Coast and Geodetic Survey, died on November 8, 1956, his 57th birthday. He was born at St. Marys, Ohio, and took his baccalaureate degree from the University of Indiana in 1921. He began his professional career as a teacher in Indiana schools. In 1926, he joined the U. S. Coast and Geodetic Survey, working chiefly in the field of tides and currents. In 1955, he was presented the Meritorious Honor Award of the Department of Commerce for his valuable contributions to science. He had been a member of AGU since 1943.

Union, Section, and Committee Activities

The Pacific Southwest Regional Committee has now organized and designated Vito A. Vanoni of the California Institute of Technology as its Chairman, with redesignation of R. Corday Counts, Jr., U. S. Weather Bureau, San Bruno, California, as Secretary.

The Pacific Northwest Regional Committee has now organized and designated Clifford A. Barnes of the University of Washington, Seattle, as Chairman, and Franklin I. Badgley as Secretary-Treasurer. This Region held its Third Annual Meeting, November 8–9, 1956, on which a report will later be published in the *Transactions*.

As noted in recent issues of the *Transactions*, the AGU moved in late June to quarters in the new building of the American Association for the Advancement of Science. Five rooms, totaling about 900 square feet on the third (top) floor of this modern building, are occupied by AGU. Occupying space with us on the third floor are offices of the American Society of Photogrammetry, the American Geological Institute, and some of the editorial offices of the American Chemical Society. Members are invited to visit the office at any time that they are in Washington. The address is: 1515 Massachusetts Avenue, N.W., Washington 5, D. C.

MEETING OF THE INTERNATIONAL ASSOCIATION OF HYDROLOGY, IUGG, AT DIJON, FRANCE, SEPTEMBER 20–26, 1956—This Association held a Symposium in Dijon, France, September 20–26, 1956. Over 100 hydrologists from more than 20 countries attended the Symposium, which dealt with Floods, Ground Water, and Evaporation. This Symposium was arranged by L. J. Tison, General Secretary of the Association, and was in commemoration of the 100th Anniversary of Darcy's Law. The location of the Symposium was especially appropriate, since it was in Dijon that Darcy developed the principles which led to the law bearing his name.

In commemoration of the Centennial of Darcy's Law, the Petroleum Branch of the American Institute of Mining, Metallurgical, and Petroleum Engineers prepared a scroll which was presented to the Mayor at Dijon at the inaugural meeting.

Following the Symposium, a field trip from Dijon to Grenoble, thence to Briancon through Lautaret Pass, and down the Durance Valley to Aix en Provence, offered an opportunity to see a meteorological station in the Alps, Fournel hydroelectric plant and groundwater recharge at Chateaurenard, as well as much other interesting work.

The more than 70 papers presented in the Symposium have been published in three volumes. Copies are for sale and may be obtained from L. J. Tison, 61 rue des Ronces, Gentbrugge, Belgium.

In addition to the undersigned, attending from the United States were L. R. Beard, Ven Te Chow, Tate Dalrymple, Fred H. Klaer, Luna B. Leopold, M. I. Rorabaugh, and David K. Todd, with the undersigned serving as Chairman.

WILLIAM E. HIATT

Special Announcements

PACIFIC SOUTHWEST REGIONAL MEETING AT SACRAMENTO, FEBRUARY 14–15, 1957—Plans for this meeting have developed rapidly, and the program is now largely set up. Interested persons should get in touch with the General Chairman for the meeting, Harlowe M. Stafford (U. S. Geological Survey, 2520 Mar-

coni Avenue, Sacramento, California), the Chairman of the Program Committee, Harvey O. Banks (Department of Water Resources, State of California, Sacramento, California), or Lloyd H. Magar (U. S. Weather Bureau, Sacramento, California) who is arranging the program in Meteorology.

THIRTY-EIGHTH ANNUAL MEETING, WASHINGTON, D. C., APRIL 29–MAY 1, 1957—Attention is called to the extended note concerning this meeting on page 663 of the October issue of the *Transactions*. Note that in general titles and abstracts of papers for the program should be sent in as soon as possible to the appropriate person and in general not later than March 5, 1957.

In the case of Meteorology, the meeting will be held jointly with the American Meteorological Society, with Ferguson Hall (U. S. Weather Bureau, Washington 25, D. C.) as General Chairman for the joint program. The closing date for titles and abstracts for the joint meteorological program is set earlier, January 25, 1957; and material relating to this should be sent to Program Chairman Hall. The meetings in Meteorology will extend to include the 2nd of May. The present plans include a symposium on the outlook for the future in meteorology, including such fields as observation and instruments, numerical prediction, local forecasting, tropical meteorology, and meteorological staffing problems. Included in the plans are general sessions emphasizing such topics as droughts, instruments, numerical weather prediction, the place of tropical meteorology in the general circulation picture, and problems of forecasting 'weather' from prognostic charts and local analysis, and the synoptics and dynamics of the higher levels of the atmosphere. Special sessions will be held on these and other topics as sufficient papers indicate.

Abstracts must be informative and concise; not more than 150 words. Longer abstracts will be cut down or omitted at the discretion of the program editor. Remember that Sections may close programs prior to March (or January 25, in the case of Meteorology), so send information in early. Complete manuscripts should be in the AGU office by April 15, with advice as to whether the paper is being submitted for the *Transactions* or only for information. If the former case, three copies, complete with figures and tables, should be sent, double-spaced, and in general accordance with AGU's "Suggestions to Authors." Also send word concerning projection equipment required. A standard-sized (3¼ x 4 inches) slide projector will normally be available, but other facilities will be provided only upon word of requirements. If you do not have experience in proper preparation of figures and tables for the making of slides, write to the AGU office requesting information on this. The one general rule, however, is to avoid crowding and attempting to show too much on one slide. More than two or three curves on one slide tend to be confusing. Use good-sized lettering.

In preparing a paper for presentation, keep in mind that the requirements are quite different from those for publication. A paper for presentation might be compared to a thread or chain, while a published paper is more on the order of a fabric. And, in presentation, keep in mind that you should face the audience and speak slowly, distinctly, and briefly, and avoid complicated mathematics. The mathematical presentation should appear in the published paper.

Block bookings have been made at three hotels as follows:

Roger Smith Hotel, Pennsylvania Avenue at 18th Street, N.W.
Willard Hotel, Pennsylvania Avenue at 14th Street, N.W.
Raleigh Hotel, Pennsylvania Avenue at 12th Street, N.W.

Make your room reservation early directly with the hotel of your choice, citing the AGU block booking if you write to one of the three hotels noted.

ELEVENTH GENERAL ASSEMBLY OF IUGG TO BE HELD IN TORONTO, CANADA, SEPTEMBER 3–14, 1957—Plans are shaping up in the various Associations for this meeting. Get in touch with the office of AGU if you plan to attend this meeting, and with the office of AGU or the appropriate Secretary (see page 663 of the October issue) if you desire to take part in the meeting by the presentation of a paper. The programs are now taking shape, and recently at the meeting of the Association of Hydrology in Dijon, France, tentative schedules were set up by the Association for the program of the various commissions and committees.